DETERMINATION OF *J-Q* LOCUS FOR MATERIAL OF REACTOR PRESSURE VESSEL WWER 440 AT CLEAVAGE FRACTURE

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ABSTRACT: Recently, series of 18 specimens of SEN(B) type and 18 specimens of SEN(T) type were tested in Nuclear Research Institute Řež with the goal to quantify the effect of shallow crack (in-plane constraint) on fracture toughness for steel 15CH2MFA of WWER 440 reactor pressure vessel, for two types of loading: bending and tension. The tests were performed at temperature near reference temperature T_0 determined according to Master Curve concept, in the brittle-ductile transition region. Specimens contained deep or shallow cracks. Values of two fracture parameters J and Q were determined. Due to different characters of stress fields found for the two types of loading, the Q-stress parameter was examined in dependence on values of normalized distance $r\sigma_0/J$. Different values of the normalized distance were examined, 2, 4, 6, 8 and 10. Based on a reasonable criterion, the J-Q locus for WWER 440 RPV steel was suggested, open for further discussion.

INTRODUCTION

In this paper, the problems associated with fracture of ferritic steel 15CH2MFA in the transition region are dealt with. Two-parameter fracture mechanics, in particular the *J-Q* approach [1,2], represents one way how to predict fracture toughness J_c for a structure, in dependence on constraint level expressed by the *Q*-stress parameter. Despite the fact that to date the RPV integrity assessments are based on a one-parameter conservative approach using only fracture toughness obtained from tests with full constraint (specimens with deep cracks, preferably under conditions of plane strain) the attempts are made how to decrease the conservatism contained in this approach by establishing and using the real fracture toughness dependence on constraint level. In this paper we focused on investigating the effect of in-plane constraint (i.e. effect of shallow cracks) on fracture toughness together with examining the effect of type of loading (bending vs. tension).

EXPERIMENTAL

Fracture toughness tests were performed on 18 specimens of SEN(B) type of dimensions (in mm) 25 (width) x 12.5 (thickness) x 120 (length) and on 18 specimens of SEN(T) type of the same dimensions, but with middle part of length 40 mm reduced so as to have dimensions 12.5 (width) x 10 (thickness) in order to reach sufficient loading capacity for failure of the specimens (Fig.1). For each loading type, three crack depths were tested: deep (a/W ~ 0.5), shallow (a/W ~ 0.16, resp. 0.17) and very shallow (a/W ~ 0.09). Thus, 6 specimens were tested for each type of loading and each type of the crack. All specimens were tested at temperature T = -98 ºC, being equal to the reference temperature T_0 determined for the steel concerned according to Master Curve concept [3]. During testing, some of the specimens, mainly those containing shallow crack, underwent small amount of ductile tearing. Summary of mean ductile tearing amounts for individual specimens are attached in the Table 1. All specimens failed by cleavage. During experiments, both CMOD and force values were recorded. Experimental records for all specimens tested are plotted in Fig.2.

TABLE 1: Ductile tearing amounts and fracture toughness values for individual specimens

Loading type (specimens No.)	a/W	ductile tearing [mm]	fracture toughness J_c [kJm^{-2}]
bending (18 – 23)	0.09	0, 0.04, 0.27, 0.34, 0.34, 0.41	97.6, 115.5, 369, 366, 420.7, 460.4
bending (26 – 31)	0.16	0.21, 0.13, 0.34, 0.21, 0.06, 0.08	381.5, 245.5, 370.3, 343.6, 122.1, 170.9
bending (32 – 37)	0.5	0, 0, 0, 0.19, 0, 0	38.9, 23.5, 54.5, - , 51.5, 24.2
tension (38 – 43)	0.09	0.4, 0.33, 0, 0.22, 0.31, 0.41	537.8, 320.5, 76.3, 231, 387, 434
tension (44 – 49)	0.17	0.11, 0.11, 0.11, 0.08, 0.09, 0.11	223.5, 217, 195, 184.8, 281.4, 192
tension (50 – 55)	0.5	0, 0.06, 0, 0, 0.07, 0	101.5, 237.3, 97.9, 158.7, 197.2, 105

MATERIAL PROPERTIES

In FE calculation the following values (relevant to temperature T = -98 ºC) of material parameters were used: the yield stress σ_0 = 618.2 MPa, ultimate tensile strength R_m = 792.9 MPa, uniform elongation A_m = 10.5 %, Young modulus E = 210.0 GPa and Poisson number ν = 0.3.

NUMERICAL ANALYSIS OF THE EXPERIMENTS

2D and 3D elastic-plastic analyses of the experiments were performed, using FE codes SYSTUS and ANSYS. While for tension specimens the 2D generalized plane strain calculations produced force vs. CMOD curves that were in satisfying accordance with the experimental ones, for bending specimens large discrepancies appeared. The discrepancies disappeared after performing 3D calculations for the bending specimens.

In 2D (quadratic) meshes, the crack was modeled as a notch of radius 1 μm, the element size nearest to the crack tip was 0.1 μm. In 3D (quadratic) meshes the sharp crack was modeled, with radial type of mesh in the first layer of elements adjacent to the crack front and with element size in the vicinity of crack front of 0.01 mm.

Elastic-plastic behavior of specimens was modeled using flow theory of plasticity with von Mises yield surface and isotropic hardening. Large strains were used.

Methods used in determination of fracture toughness J_c and Q-stress parameter

Since the experimental records within one group of six specimens representing certain combination of loading type and relative crack depth did not exhibit large scatter (Fig.2), only one FE calculation was performed for each group. Fracture toughness J_c was determined as a critical value of J-integral at the moment of fracture, the CMOD value being used as a criterion. In all cases the accordance between experimental and calculated curve force vs. CMOD was either good or at least acceptable. For determination of J-integral either the 2D Rice contour integral method or the 3D G-θ method [3] was applied. J-values were determined always on the symmetry plane.

The Q-stress parameter was determined in accordance with J-Q theory using the definition of Q-stress as follows (σ_{yy} means stress opening the crack, σ_0 denotes the yield stress):

$$Q = \frac{\sigma_{yy} - \left(\sigma_{yy}\right)_{SSY,T=0}}{\sigma_0} \quad \text{at } \theta = 0 \text{ and } 2 \le r\sigma_0/J \le 10,$$

where r is distance from the crack front and $\theta = 0$ means that Q is calculated on the symmetry plane.

FE evaluations of experiments

In FE evaluation of experiments small amounts of ductile crack growth were neglected. For tension specimens, practically no path dependence of J-integral was found.

For bending specimens, large path or parameter dependence of J-integral was initially found. This path dependence was later partially removed by considering only paths which do not cross the region of large plasticity arising due to the support of the specimen loaded by 3P-bending (in this region plasticity arises as a consequence of large compressive stresses and is not related to the crack growth).

Fracture toughness values for individual specimens are summarized in Table 1. To determine the Q-stress parameters, variations of stress opening the crack vs. normalized distance $r\sigma_0/J$ were calculated, together with 2D SSY (with T-stress = 0) reference solution. The resulting variations of Q-stress parameter vs. $r\sigma_0/J$ are presented (Figs.3–6).

From Figs.3–6 it is obvious that while Q-stress parameters for tension specimens scale well for smaller values of $r\sigma_0/J$ (within some interval enclosing value $r\sigma_0/J = 2$), the Q-stress parameters for bending specimens scale well for larger values of $r\sigma_0/J$ (within some interval enclosing value $r\sigma_0/J = 8$). In particular, from results for tension specimens with $a/W = 0.09$ (Fig.5) it is seen that Q-stress parameters scale well in interval approximately equal to (1.3, 2.2) where the correct relationship between loss of constraint and loading level (at fracture) takes place: Q is the more negative, the higher is the load that the specimen withstood. Out of this interval this relationship is no more valid.

Also for bending specimens the correct relationship between loss of constraint and loading level (at fracture) is found in some interval of values $r\sigma_0/J$, but the most pronounced loss of constraint occurs in interval approximately equal to (6, 10).

Accepting reasonable criterion that values of Q should be determined in a point (or in an interval, if it is possible) where the scaling effects are most pronounced, the logical conclusion is to calculate the Q-stress parameters in

$r\sigma_0/J = 2$ (or in some point near to 2) for tension specimens and to calculate the Q-stress parameters in $r\sigma_0/J = 8$ (or in some point near to 8) for bending specimens.

To express the obtained findings in terms of J-Q locus, we attach here two plots of J-Q locus: J-Q locus with Q evaluated in $r\sigma_0/J = 2$ for both tension and bending (Fig.7), and J-Q locus with Q evaluated in $r\sigma_0/J = 2$ for tension specimens and in $r\sigma_0/J = 8$ for bending specimens (Fig.8).

Similar J-Q loci as in Fig.8 were constructed also for Q evaluating in $r\sigma_0/J = 2$ for tension specimens and $r\sigma_0/J = 6$ or 10 for bending specimens, with no significant change in the shape of the locus.

CONCLUSION

In this paper two types of J-Q locus for steel of reactor pressure vessel WWER 440 were constructed, in the brittle-ductile transition region. In the first type of J-Q locus (Fig.7), the Q-stress parameters were evaluated in $r\sigma_0/J = 2$ for both tension and bending loading. Within this approach the (J_c, Q) points considered all together do not exhibit common functional dependence. In the second type of locus (Fig.8), the Q-stress parameters are evaluated in $r\sigma_0/J = 2$ for tension loading and in $r\sigma_0/J = 8$ for bending loading. Within this approach all (J_c, Q) points cumulate along a curve, with a relatively small scatter. Moreover, intervals of values $r\sigma_0/J$ exist, within which the shape of J-Q locus does not change significantly when a different value $r\sigma_0/J$ from the interval is selected. Due to these features, the second type of J-Q locus seems to be a more suitable for further possibilities of application in reactor pressure vessel integrity assessment.

REFERENCES

[1] O'Dowd, N. P., Shih, C. F. (1991), *J. Mech. Phys. Solids* **39**, No.8, 989

[2] O'Dowd, N. P., Shih, C. F. (1992), *J. Mech. Phys. Solids* **40**, No.5, 939

[3] ASTM Standard Test Method for Determination of Reference Temperature, T_0, for Ferritic Steels in the Transition Range, ASTM E 1921-97

Acknowledgement: The support of the Grant Agency of the Czech Republic through grant No.106/00/1347 is gratefully acknowledged.

FIG.1: Geometry of the tension and bending specimens

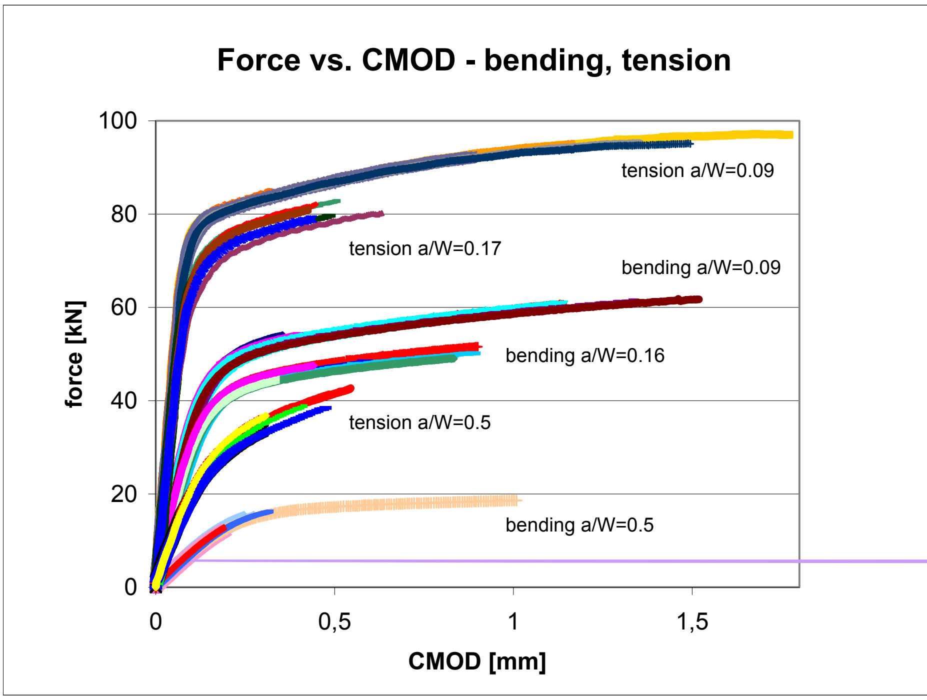

FIG.2: Experimental records - CMOD vs. force values

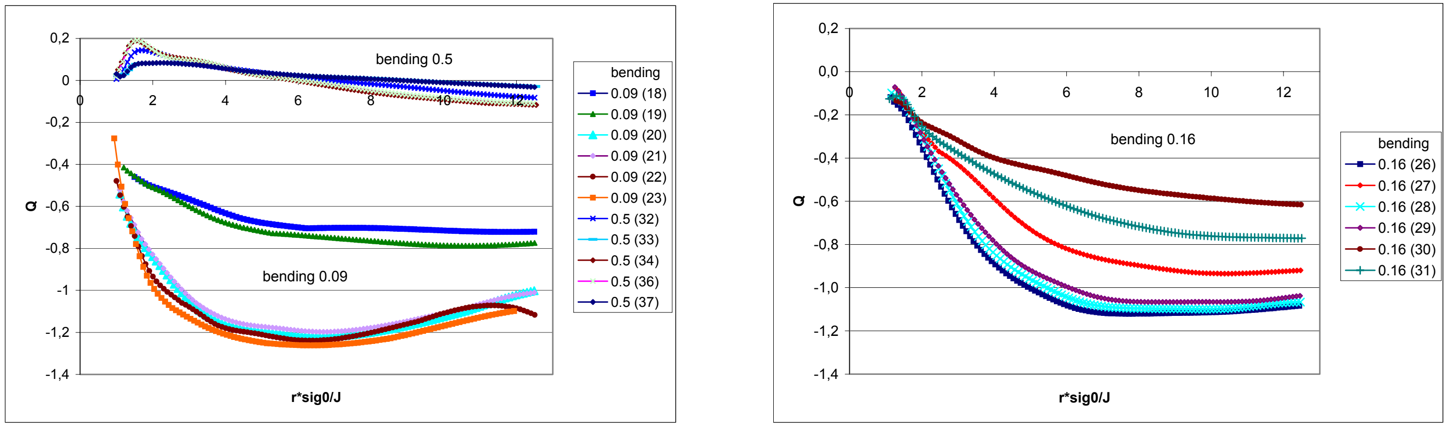

FIG.3-4: The Q-stress parameter vs. normalized distance $r\sigma_0/J$ for **bending**

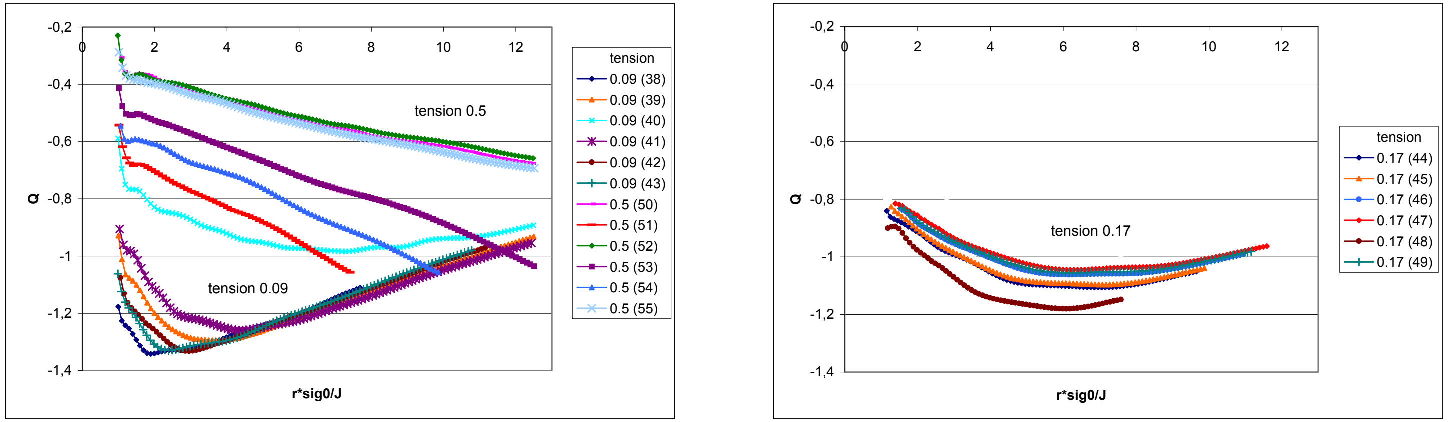

FIG.5-6: The Q-stress parameter vs. normalized distance $r\sigma_0/J$ for **tension**

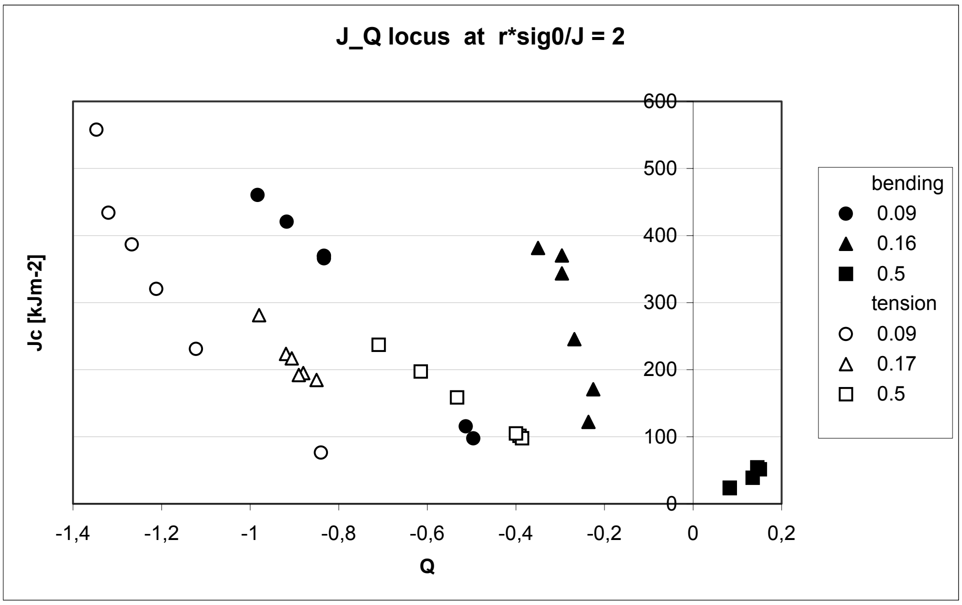

FIG.7: Conventionally determined *J-Q* locus

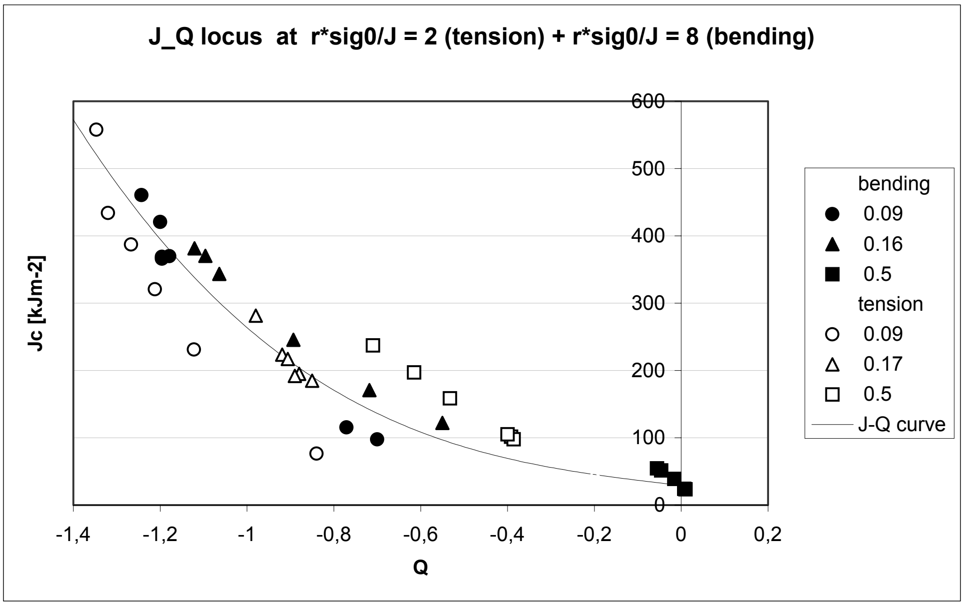

FIG.8: Resulting *J-Q* locus