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CRACK INITIATION UNDER STATIC LOADS INCLUDING THE INFLUENCE OF RESIDUAL WELDING STRESSES

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***Abstract**. Starting from the basic approaches for the reduction of ultimate strain for steel with increasing hydrostatic stress tensor a function is derived which reflects the different influences on ultimate strain abetting brittle fracture. This function, which via stress state includes the influence of residual stresses, e.g. due to welding, is a tool for predicting the formation of the crack. Nonlinear FE-analyses including a welding simulation macro are performed to describe the stress-strain situation up to the fracture state in component tests.*

1 INTRODUCTION

The steadily growing demands on span, size and transparency of steel constructions result in structures with increasing span. The large stress resultants which are due to this development necessitate thick cross-sections and/or high strength steels. The latest enhancements of the steel production provide products which satisfy both of these requirements and at the same time have largely improved toughness properties. This development has to be taken into account in the design standards. Fracture mechanics is utilized for this purpose as the basis of EN 1993-1-10. Because the presence of a crack is a sine qua non for the application of fracture mechanics such a flaw of defined size had to be assumed for the steel structure as the basis of EN 1993-1-10. This assumption, however, is contradictory to the normative regulations for the execution of steel structures, e.g. EN ISO 5817 and EN 1090-2, which do not allow a visible crack or cracks indicated by additional non-destructive-testing. Since the execution standards thus conflict with cracks assumed in the design standards there is a need to explain crack initiation due to static load. The experience shows that with this explanation multi-axial welding residual stresses and other negative influences have to be considered [1]. The following investigation is due to the great variety of influencing parameters confined to non-alloy and low alloy steel grades S235 to S355 predominantly applied in civil engineering.

2 WELDING RESIDUAL STRESSES

Since steel structures are almost always welded, the welding residual stresses have to be taken into account with the investigation of crack initiation. The welding residual stresses are calculated using a Finite Element Model (FEM). Here it is sufficient to uncouple the processes by first calculating the temperature field, and then with the temperature field as input the stress field. This is due to the fact that the results of the calculation of the temperature field strongly influence those of the stress calculation, but those of the stress calculation have almost no influence on those of the calculation of the temperature field. Fig. 1 shows the uncoupling of the sub-models when neglecting transformation.

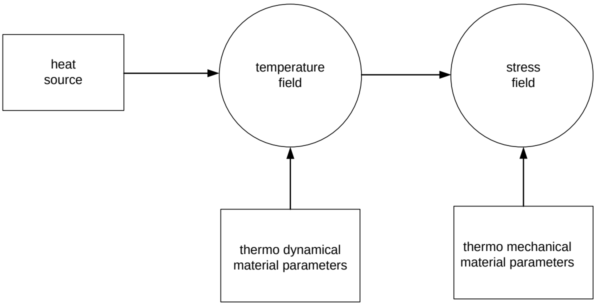

Fig. 1: Uncoupling of the sub-models for a simplified calculation of residual stresses

The calculation of the temperature field is performed on the basis of a heat conduction model because the thermal conduction in the material which is emanating from the welding heat source dominates the development of the temperature field. Large strains are accounted for by also considering non-linear terms in the displacement-distortion-relation in the subsequent calculation of the stress field. Due to the large plastic strains at high temperatures, real stress-strain-relations are applied.

Temperature dependent material parameters: Since thermo-dynamical as well as thermo-mechanical material parameters of non-alloy and low alloy steels strongly depend on the temperature, the governing material parameters have to be applied as functions of temperature for the numerical determination of residual stresses after welding.

The FE-program ANSYS is used for the numerical calculation of the welding residual stresses. For this purpose, a welding simulation macro was developed, which for almost any structure easily calculates temperature field and stress field induced by the welding process [2]. The temperature dependent material parameters for grade S 335 and similar steels (Figures 2, 3, 4) are the basic input data for this macro.

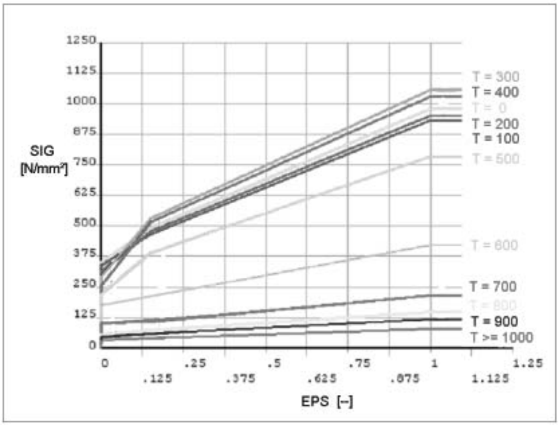

Fig. 2: Temperature dependent σ-ε-curves for S355J2+N used in the FE-analysis

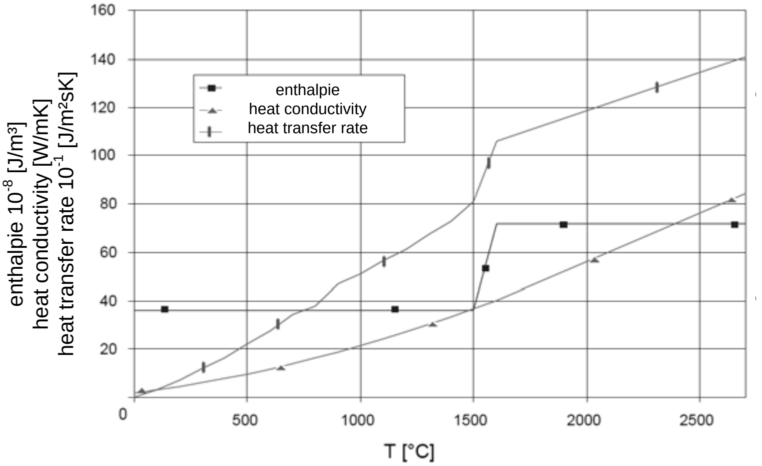

Fig. 3: Thermo-dynamical material parameters used in the FE-analysis

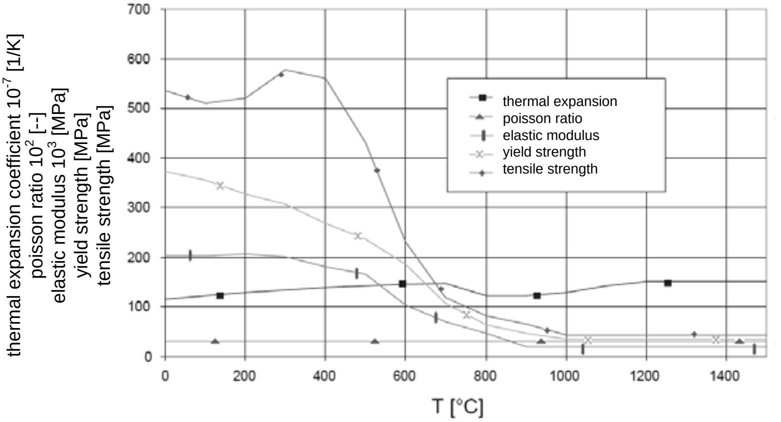

Fig. 4: Thermo-mechanical material parameters used in the FE-analysis

The temperature distribution obtained in a welding test with a fillet weld (MAG, energy P = 6417 W (k = 0,9)) is compared with the results from the FE-analysis for the same configuration. The fusion zone obtained from the calculation is compared with that from the test for verifying the calculation of the temperature field. Fig. 5 shows this comparison of the temperatures obtained in the numerical calculation with the etched macro-section of the welding test. The weld pool with a maximum root penetration of 1.8 mm in both cases shows a very good conformity. Table 1 gives the values of temperature distributions from the welding test and the FE-analysis, which also agree very well.

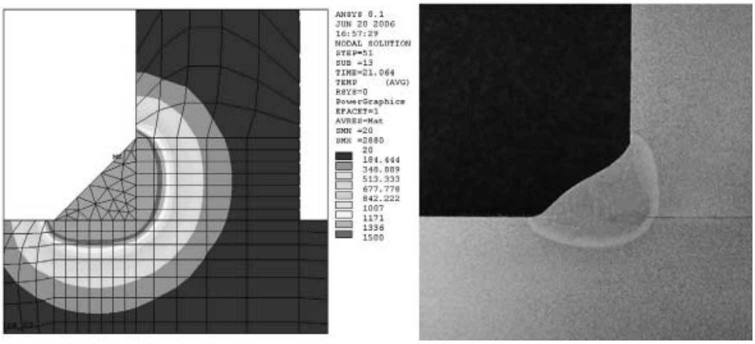

Fig. 5: Comparison of fusion depth from FE and welding test

Table 1: Comparison of temperature distribution from FE and welding test

Temperature	distanced from root point to the left [mm]		distance from root point to the top [mm]	
	test	FEM	test	FEM
340°C	12,0	12,5	10,5	12,5
280°C	13,0	13,5	12,0	13,5
220°C	14,5	14,5	14,0	14,5

3 CRITERION FOR CRACK INITIATION

Under static load, a crack develops exactly when the first principal strain ε_1 reaches a critical value. This assumption is the basis of the following considerations and was already investigated in [3], [4] with regard to the influence of multiaxiality. In this context there are approaches to assume a decrease of critical strain ε_{crit} with increasing multiaxiality of the stress condition (SMCS – Stress Modified Critical Strain) where the multiaxiality M is defined by the ratio of mean stress σ_m to equivalent stress σ_V:

$$\varepsilon_{crit} = SMCS = K_\varepsilon \cdot e^{-B \cdot M} \tag{1}$$

$$M = \frac{\sigma_m}{\sigma_v} \tag{2}$$

Hancock and Brown [4] for example use the value B = 1.5 for steel. In Fig. 6, the critical strain ε_{crit} is depicted versus the multiaxiality M for different values of the factor K_ε.

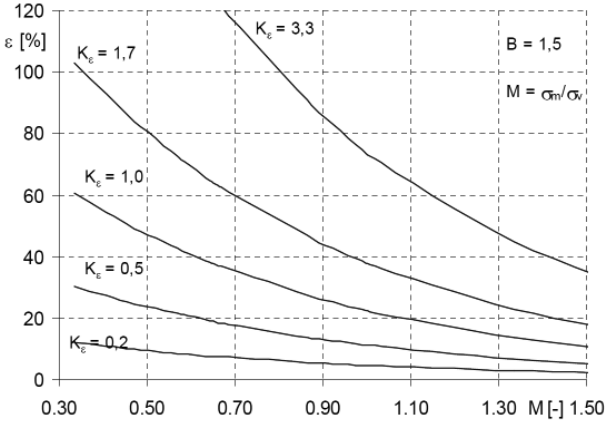

Fig. 6: Influence of multiaxiality M on the critical strain at failure ε_{crit} (SMCS)

The observation of crack initiation in tensile tests which are only different with regard to the notch geometry of the specimens (Fig. 7) in comparison with the results of the associated FE-analyses is performed to verify equation (1). The factor K_ε is obtained with the tests at ambient temperature. For the round bar tensile specimens (Fig. 7) the failure is defined as crack initiation when the crack starts from inside.

Table 2 gives the first principal value ε_1 of true strain at which crack initiation occurs, the corresponding multiaxialitiy M and the location of crack initiation for the tensile specimens Z1 to Z4. Fig. 8 with the plot of ε_1 versus M for the 4 tests shows that equation (1) with K_ε = 3,3 fits the results. With the test specimens Z1, Z2 and Z3 the multiaxiality becomes decisive and the fracture accordingly starts from inside whereas the fracture for specimen Z4 starts from outside due to the sharp notch.

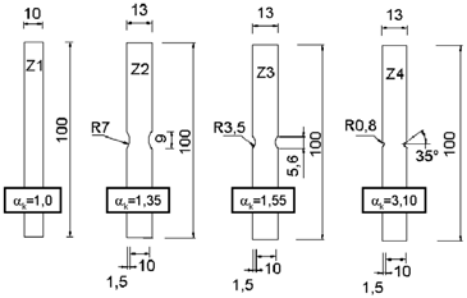

Fig. 7: Dimensions of the tensile specimens for the tensile tests

Table 2: strains ε_1 at crack initiation and corresponding multiaxiality M.

Specimen	test temperature [°C]	location of crack	strain ε_1 at crack initiation	multi-axiality M
Z1	20	inside	1,15	0,76
Z2	20	inside	0,79	0,91
Z3	20	inside	0,72	1,05
Z4	20	outside	1,15	0,46

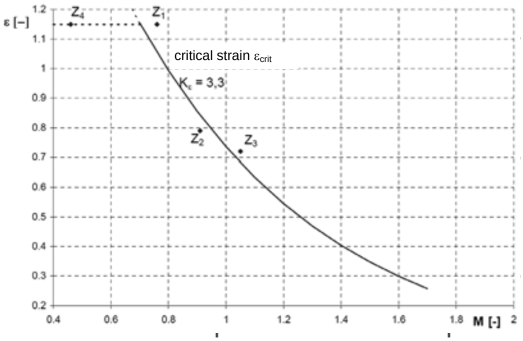

Fig. 8: Results of the tests with notched tensile specimens

5 TESTS FOR IMPROVING THE CRITERION FOR CRACK INITIATION

The critical strain ε_{crit} not only depends on multiaxiality M but also on other influences X_i. The essential ones are:

X1 = toughness expressed by transition temperature obtained from Charpy impact test
X2 = strength expressed by yield stress R_{eH} or $R_{p0,2}$
X3 = material thickness t
X4 = component temperature ϑ
X5 = change of material microstructure due to welding
X6 = rate of stress increase, cold-working, zinc coatings

Numerous component tests and FE-analyses, which are documented and evaluated in [5], were performed to extend equation (1) in order to include the influences X_i by presenting the factor K_ε as a product according to equation (3) of factors K_i depending on the parameters X_i,. Figures 9 and 10 show the functions $K_i(X_i)$ for the influences X_1 to X_4. With the assessment $K_5 = 1$ the influence of changes of material microstructure due to welding was ignored. Since the tests were performed with slow loading rate and the material was neither cold-worked nor zinc coated $K_6 = 1$.

$$K_\varepsilon = \prod_i K_i = \prod_i K(X_i) \qquad (3)$$

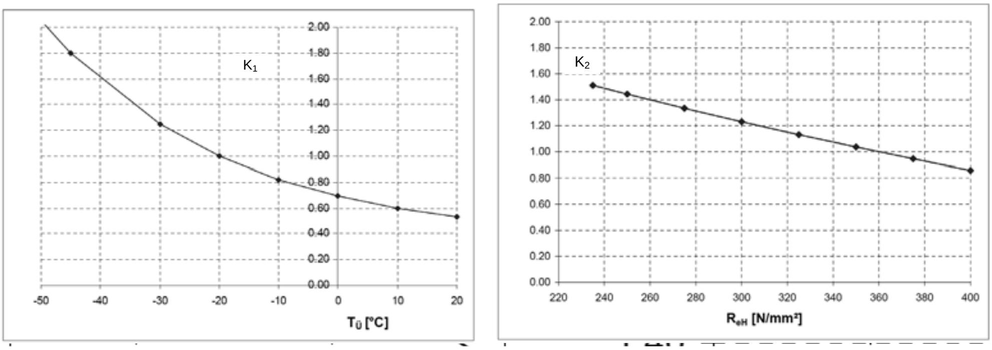

Fig. 9: Influence of the transition temperature K_1 and the yield strength K_2 on K_ε

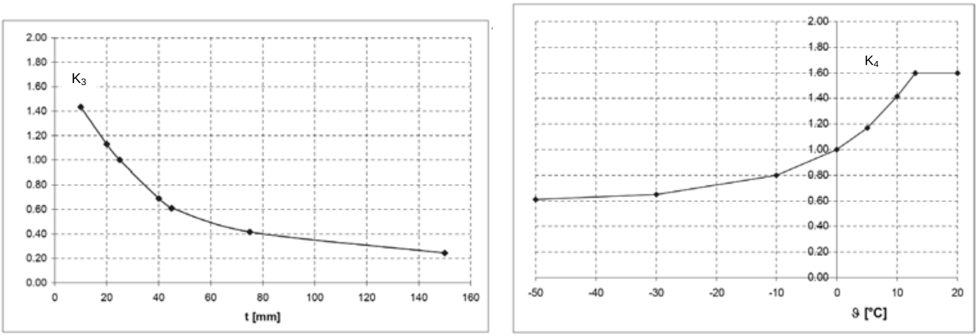

Fig. 10: Influence of the material thickness $K_3$and the component temperature K_4 on K_ε

6 COMPARISON WITH EN 1993-1-10

For comparing the results of the crack initiation criterion (1) with those of EN 1993-1-10, critical strains ε_{crit} at failure according to equation (1) are calculated with maximum allowable thicknesses t according to EN 1993-1-10 for the utilization factor $\sigma_{Ed}/f_{y(t)} = 0,75$. These calculations are performed with the multiaxiality M = 1,0 as an unfavorable assumption for two different steel grades S235 and S355, different toughness values as expressed by X_1 and two different temperatures 0°C and 30°C. The results of these calculations are compiled in Table 3. All strains at failure ε_{crit} are about 10%. For other multiaxialties M, the calculated strains at failure are also within such narrow limits.

Table 3: Calculated strains at failure ε_{crit} for limit cases according to EN 1993-1-10 for M = 1,00

Steel grade	$X_1(T_{ü})$ [°C]	$X_2(R_{eH})$ [MPa]	$X_3(t)$ [mm]	$X_4(\vartheta)$ [°C]	$K(X_1)$ [---]	$K(X_2)$ [---]	$K(X_3)$ [---]	$K(X_4)$ [---]	K [---]	M [---]	ε_{crit} [---]
S235JR	20	240	50	0	0,53	1,49	0,57	1,00	0,45	1,0	0,10
S235JR	20	240	30	-30	0,53	1,49	0,88	0,65	0,45	1,0	0,10
S235J0	0	240	75	0	0,69	1,49	0,42	1,00	0,43	1,0	0,10
S235J0	0	240	40	-30	0,69	1,49	0,69	0,65	0,46	1,0	0,10
S235J2	-20	240	105	0	1,00	1,49	0,31	1,00	0,47	1,0	0,10
S235J2	-20	240	60	-30	1,00	1,49	0,50	0,65	0,48	1,0	0,11
S355JR	20	360	35	0	0,53	1,00	0,78	1,00	0,41	1,0	0,09
S355JR	20	360	15	-30	0,53	1,00	1,27	0,65	0,44	1,0	0,10
S355J0	0	360	50	0	0,69	1,00	0,57	1,00	0,39	1,0	0,09
S355J0	0	360	25	-30	0,69	1,00	1,00	0,65	0,45	1,0	0,10
S355J2	-20	360	75	0	1,00	1,00	0,42	1,00	0,42	1,0	0,09
S355J2	-20	360	40	-30	1,00	1,00	0,69	0,65	0,45	1,0	0,10
S355K2/M/N	-30	360	90	0	1,25	1,00	0,36	1,00	0,44	1,0	0,10
S355K2/M/N	-30	360	50	-30	1,25	1,00	0,57	0,65	0,46	1,0	0,10
S355ML/NL	-50	360	130	0	2,05	1,00	0,27	1,00	0,55	1,0	0,12
S355ML/NL	-50	360	75	-30	2,05	1,00	0,42	0,65	0,55	1,0	0,12

7 CONCLUSION

Crack initiation occurs when the first principal strain exceeds a critical value ε_{crit}. This value ε_{crit} depends upon several factors which are known to contribute to brittle failure susceptibility. An already existing formula relates the critical strain ε_{crit} to the multiaxiality M which is expressed by the ratio of mean value σ_m of the three principal stresses to the von Mises equivalent stress σ_V. This formula is extended with a product of factors K_i which represent the unfavourable influences of low toughness, high strength, thick material and low temperature. These factors K_i, which are functions of the influence parameters are obtained from tests with schematic variation of the influence parameters. The effect of welding is accounted for with the welding residual stresses which contribute to the stress state and thus also influence the multiaxiality M. Changes of the microstructure of the steel are only taken into account in the calculation of the residual stresses but not in the determination of the critical strain ε_{crit}. The results of the investigation are confined to non-alloy and low alloy steel grades S235 to S355 since for higher strength materials the macro developed in this investigation for the calculation of welding residual stresses will need some modification.

The criterion presented here has been verified with several component tests which were performed for investigation of the cause of failures of structures. Because of the restricted space they are not reported here but in [5]. The application of the criterion (1) to the steel grades S235 and S355 shows that with a utilization factor $\sigma_{Ed}/fy(t) = 0{,}75$ and the unfavourable value M = 1 the critical strain ε_{crit} for all possible combinations of different toughness values and component temperatures for the maximum material thickness allowed by EN 1993-1-10 is nearly the same. Thus the criterion presented here includes the results of EN 1993-1-10 and additionally facilitates a more realistic consideration of the component situation, because no crack has to be assumed and the assumption of residual stresses included in EN 1993-1-10 is obsolete because the specific residual stress state is taken into account in the criterion.

REFERENCES

[1] Saal, H., Steidl, G., Volz, M.: *Sprödbruchsicherheit im Stahlbau*. Stahlbau 70 (2001), S. 685 697.

[2] Käpplein, S.: *Bestimmung von Schweißeigenspannungen mit der Methode der Finiten Elemente.* Diplomarbeit an der Versuchsanstalt für Stahl, Holz und Steine der Universität Fridericiana in Karlsruhe, 2006.

[3] Valtinat, G.: *Kriterium zur Erfassung der Spannungsversprödung von Werkstoffen*. Habilitationsschrift, Fakultät für Bauingenieur- und Vermessungswesen, Universität Karlsruhe, 1970.

[4] Hancock, J.W., Mackenzie, A.C.: *On the mechanism of ductile failure in high-strength steels subjected to multi-axial stress states*. J. Mech. Phys. Solids, 1976, Vol. 24, pp. 147 to 169, Pergamon Press, Great Britain.

[5] Volz, M., *Die Rissentstehung in statisch beanspruchten Stahlkonstruktionen unter Berücksichtigung von Schweißeigenspannungen*. Berichte der Versuchsanstalt für Stahl, Holz und Steine der Universität Fridericiana in Karlsruhe, 5. Folge Heft 22, Karlsruhe, Germany, 2009.