# TESTS OF FULL SCALE STRUCTURAL MEMBERS FOR THE VERIFICATION OF ANNEX C, TO EUROCODE 3-2

B. Kalinowski*, P. Langenberg*, W. Dahl*, G. Stötzel**, N. Stranghöner*** and G. Sedlacek***

The Annex C concept for the choice of material for the design against brittle fracture, Eurocode 3, part 2, is described shortly. Results of new large scale tests on 80mm thick steel plates with welded structural details like stiffeners and surface cracks are presented with regard to the verification of Annex C. In addition crack growth curves were measured on these specimen with the help of an ACPD potential drop technique and compared with results from small scale specimen and literature.

## INTRODUCTION

According to the basic principles of the Eurocodes the design resistances of the steel members in Eurocode 3 „Design of steel structures“ have been calibrated to the results of experimental tests to achieve sufficient reliability. The method for the choice of material to avoid brittle fracture of steel members (Annex C, EC3-2) is based on a fracture mechanics concept. This method has been verified up to now by the statistical evaluation of 19 large scale tests with through-thickness cracks only and various steel grades according to Annex Z of EC3. The results of the large scale tests presented in this paper are used to improve the safety elements of Annex C of EC 3.

The work has been supported by the Deutsche Forschungsgemeinschaft. The support is gratefully acknowledged.

* Institute of Ferrous Metallurgy, ***Institute of Steel Construction, RWTH Aachen
**Ingenieurbüro Grassl, Berlin

## ANNEX C OF EUROCODE 3

The new concept for the choice of material to avoid brittle fracture is based on a fracture mechanics concept (1-3). The concept takes account of the parameters influencing brittle fracture as there are the yield strength, temperature, applied stress, plate thickness and stiffeners. The method is based on a comparison between the temperature action $T_{Ed}$ on the structure and the material resistance $T_{Cd}$ (figure 1). Temperature action is depending on climatic conditions like lowest air temperature and radiation effect. The material resistance $T_{Cd}$ describes the resistance of a structural detail to brittle fracture. Safe behaviour can be assumed as long as

$$T_{Ed} \geq T_{Cd} \qquad (1)$$

The fracture mechanics model is based on a „worst-case scenario". In welded components it is always possible, that small initial cracks in the welded zones with stress concentrations grow under fatigue. If the crack depth becomes critical, brittle fracture can occur. From this scenario fracture mechanics models for typical structural steel fatigue classes with semielliptical surface cracks have been developed. The assumed initial crack depth $a_0$ is dependant on the plate thickness:

$$a_0 = 0{,}5 \cdot \ln(t / t_0) \qquad t_0 = 1\text{mm and } a/c = 0{,}4 \qquad (2)$$

This crack is defined as the maximum size that may be overlooked at regular inspections of a bridge. With regard to inspection periods of a bridge of about 25 years, which is equivalent to ¼ of the lifetime or 500.000 load cycles from $2*10^6$ load cycles associated with the fatigue strength $\Delta\sigma_c$ from Eurocode 3, the critical crack depth $a_d$ shall not be reached. The crack growth from $a_0$ to the critical crack length $a_d$ during the inspection period is calculated with the Paris-Law.

To calculate $T_{Cd}$ the fracture mechanics safety concept is applied to this critical defect. The concept is based on the CEGB-R6 method (4), Master-curve-concept (5) and a modified Sanz-correlation (6). The partial safety element $\Delta T_a$ has been calculated from a statistical evaluation of wide plate large scale tests (3) on DECT specimen.

## EXPERIMENTS

In order to improve the safety element $\Delta T_a$ a series of 60 member tests with two fine grained steel grades S 355 M and S 460 M were carried out at the Institute of Ferrous Metallurgy. The specimens represent typical welded details of the fatigue resistance catalogue of EC3 (figure 2).

The tests are carried out in two steps to provide information both on the behaviour during fatigue at room temperature and on the failure behaviour under static tensile loading in the brittle fracture regime. First a fatigue crack (starting from an initial artificial crack similar to the initial crack assumed in Annex C) positioned in the base plate closed to the weld toe is monitored under cyclic loading. After reaching a calculated crack depth, the specimen is cooled down to a temperature in the brittle fracture regime and tested in a static tension test. The aims of the fatigue tests and the static tension tests at low temperatures are:

- Determination of crack growth curves (da/dN-curves)
- Investigation on the crack growth caused by 500.000 load cycles at a stress range according to the detail class $\Delta\sigma_c$ of Eurocode 3.
- Determination of the load carrying capacity in the brittle fracture regime
- Verification of the procedure in Annex C, EC3

The initiation and the growth of the depth of the crack were measured with the help of a potential drop method. For the application at large scale specimen an alternating current (ACPD) method was used. The change of the potential was measured at eigth positions in total, five at the crack, one at the opposite side of the weld, one at a position on the specimen without crack and weld and one at an unloaded, neutral specimen outside the test machine (check of the signal drift). The signal was recorded during the whole fatigue process. For the calibration of the method and to mark certain positions lines of rest were produced.

From the starter notch a fatigue crack from a $\Delta\sigma$ somewhat higher than the fatigue class was started. After detection of a small amount of crack growth this position was marked with a line of rest. After that 500.000 load cycles at a stress range according to the fatigue detail classes of EC3, part 2, were applied (table 1).

TABLE 1: Detail categories and fatigue strength $\Delta\sigma_c$ for different types of attachments

| Detail | $\Delta\sigma_c$ acc. EC3 |
|---|---|
| reference plate | 160 |
| longitudinal attachment | 71 |
| transverse attachment | 71 |
| reinforcing plate | 56 |
| reinforcing plate acc. DS 804 | 56 |
| horizontal attachments | 71 |

The end of fatigue loading was marked for the detection of the amount of crack growth in comparison to the theoretical calculation according to Annex C. After that the crack growth was further monitored until a calculated critical crack depth for the temperature of the static tension test was reached. The mean stress $\Delta\sigma$ was defined at 0.5 $f_y$. The static tension tests were carried out at temperatures between -120°C and - 100°C in the brittle fracture regime below net section yielding.

## RESULTS

### Verification of annex C, Eurocode 3

The verification of the Annex C procedure is given in figure 3. The experimental test temperature $T_{exp}$ of the static tension test is compared with the calculated temperature $T_{mod}$, where brittle fracture can occur. In the calculation the safety element $\Delta T_a$ was neglected in the first step. Tests, where net section yielding occured before brittle fracture, have not been taken into account. Compared with already existing tests on wide plates with double edge notches (DECT) the new tests with surface defects and attachments show a good correspondance with the calculated values and in most cases a safe behaviour. For the fracture mechanics calculation procedure the geometry correction factor for the crack according to Raju-Newman (9) and correction factors for the geometry of the attachments from Finite Element Calculations (10) were used.

Fatigue Tests

An example of a crack growth curve for a specimen with a transverse attachment is shown in figure 4. The actual crack depth was calculated from the calibration curve $\Delta U=f(\Delta a)$. For the calculation of $\Delta K$ the above mentioned correction factors were used. The experimental values of da/dN were calculated according to ASTM E 647-88a with the secantmethod. Small signal deviations of the Potential were reduced by calculating a gliding average over five points.

The measured values are compared with the experimental values C and m taken from small scale tests and literature. A quite good correspondance can bee seen. The result can be found sligthly on the unconservative side compared with crack growth from small scale tests and calculation according Annex C. A possible explanation are secondary stresses caused by the welding process.

## REFERENCES

(1) Eurocode 3: Design of steel structures, Part 2: „Steel Bridges“, ENV 1993-2, 1997, CEN European Commitee for Standardisation

(2) Background Document to Eurocode 3, Part 2, Chapter 3, Doc.No. II.3.1, Choice of steel material to avoid brittle fracture, May 1997

(3) Stranghöner, N.; Sedlacek, G.; Stötzel, G.; Dahl, W.; Langenberg, P.: The new Eurocode 3, Part 2, Annex C-Approach for the Choice of Steel Material to Avoid Brittle Fracture, roc. of the Seventh (1997) International Offshore and Polar Engineering Conference, Honolulu, USA, 1997, S. 551-556

(4) Milne, I., Ainsworth, R.A., Dowling, A.R., Steward, A.T.: Assessment of the integrity of structures containing defects, CEGB-R/H/R6 - Rev. 3, UK, 1986

(5) Wallin, K.: Methology for the Selecting Charpy Toughness Criteria for Thin High Strength Steels, Part I-III: Determining the Fracture Toughness, Jernkontorets Forskning, Nr. 4013/89, TO40-05, Nr.4013/89, TO40-06VTT, Nr. 4013/89, TO40-31, Manufacturing Technology, Finland

(6) Sedlacek, G.; Dahl W.; Stötzel, G.; Liessem, A.: Improvement of the Methods given in Eurocode 3, Annex C, for the Choice of Material to Avoid Brittle Fracture: Background and Revised Draft, IIW-Document X-1274-93, 1993

(7) Newman, J.C.; Raju, I.S.: An Empirical Stress Intensity Factor Equation for the surface Crack, Engineering Fracture Mechanics, Vol. 15, No. 1-2, pp. 185-192, 1981

(8) Schäfers, M.: Institute of Steel Construction, RWTH Aachen, unpublished

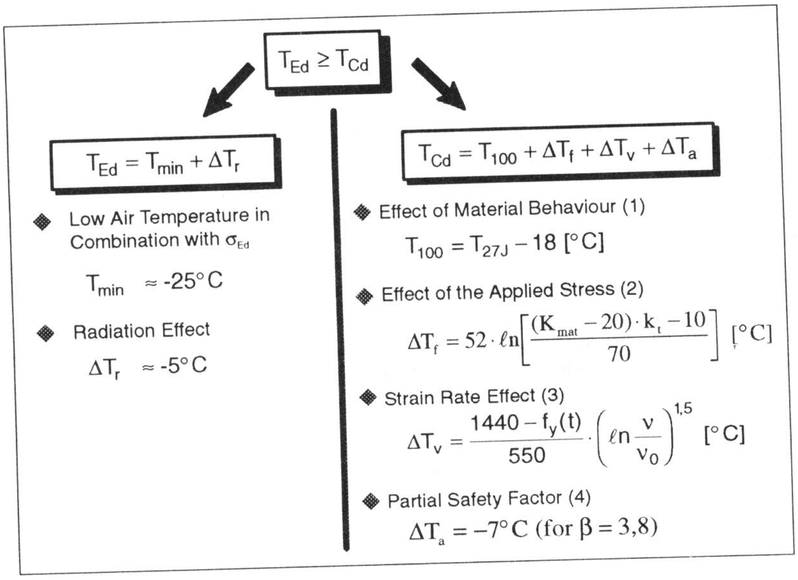

Figure 1: Concept of Annex C, Eurocode 3, part 2

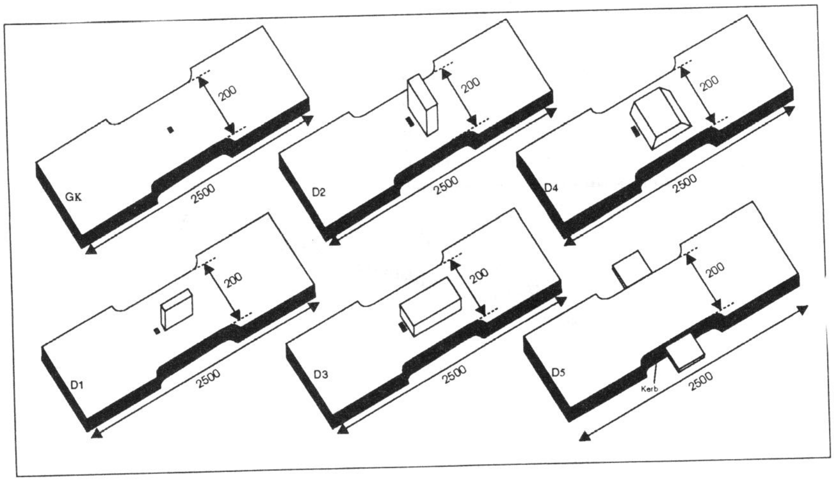

Figure 2: Large scale specimen with different welded attachments and surface cracks

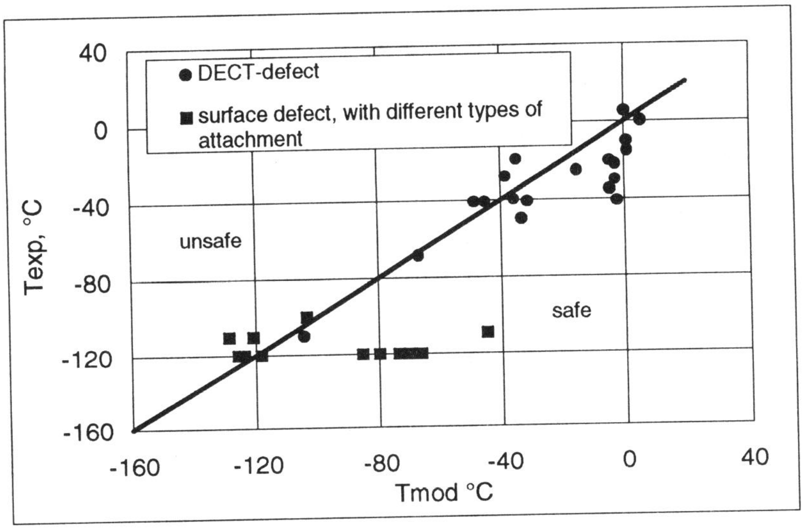

Figure 3: Experimental test temperature $T_{exp}$ as a function of the calculated characteristic brittle failure temperature $T_{mod}$

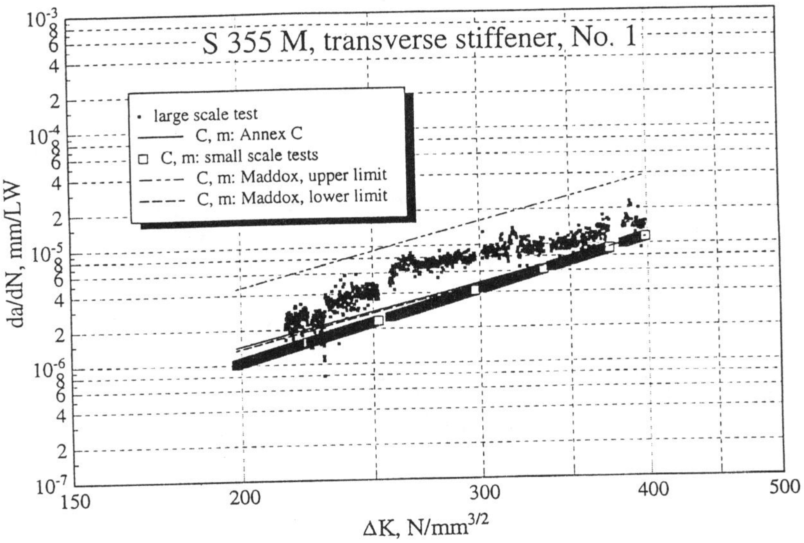

Figure 4: Crack growth curve of a large scale specimen, steel grade S 355 M, compared with different experimental C and m