Cleavage Fracture of an Eurocode 3 Structural Steel S460N Type

J. M. Flores, A. Valiente and M. Elices

Departamento de Ciencia de Materiales. Universidad Politécnica de Madrid
Escuela Técnica Superior de Ingenieros de Caminos, Canales y Puertos
Ciudad Universitaria, s/n, 28040–Madrid, Spain

ABSTRACT*: The design of steel structures in civil engineering is dealt with by Eurocode 3 paying special attention to brittle failure and fracture toughness of the steels typified for these structures. This work examines the cleavage fracture of an S460N steel type from a combined view, theoretical and experimental, regarding the effect of temperature and plate thicknesses on fracture toughness. The experimental results are explained on the basis of the weakest link model and the master curve, but in addition to this, it is inferred from the tensile behaviour of the steel that the effect of temperature on fracture toughness is transmitted by yield strength. This conclusion is corroborated by the experimental results.*

INTRODUCTION

The preservation and control of structural integrity is becoming a basic condition of structural design. Classical stress analysis cannot provide the theoretical support for this purpose and must be complemented by Fracture Mechanics. Following this trend Eurocode 3 [1] designed rules against non ductile failure. As an essential part of these rules concerning brittle failure, Eurocode 3 attributes fracture toughness values to a number of typified structural steels as a function of temperature, plate thickness and strain rate [2].

The weakest leak model for cleavage fracture [3] provides a sound basis to account for the influence of temperature and plate thickness on fracture toughness of structural steels. This approach predicts a three-parameter Weibull probabilistic distribution for the fracture toughness values, which are a potential function of thickness with an exponent of –1/4. The agreement of these predictions with the experimental data requires only an empirical amendment, consisting of the substitution of fracture toughness by its excess above a threshold toughness [4], so that the Weibull distribution becomes truncated. The shape parameter (Weibull slope) is equal to 4 as a theoretical result, the threshold toughness is equal to 20 $MPam^{1/2}$ for ferritic steels as an empirical fact universally admitted [5, 4, 6], and the scale parameter is a function of temperature, for which the weakest leak model states no condition other than that of its being characteristic of the steel. However, for ferritic steel the existence has been shown of a master curve, i.

e., a universal function of temperature dependent on a unique material constant, to be experimentally determined [6, 7]. Since the function is the sum of a constant term and an exponential one, the material constant can be viewed as the temperature at which the scale parameter takes a predetermined value for a given thickness, for example, 100 $MPam^{1/2}$ for 25 mm.

This work examines the influence of temperature on the cleavage fracture of a high strength, medium toughness structural steel S460N EN 10113. Tensile and fracture tests of the steel were carried out within a temperature range of practical interest for the service conditions covered by Eurocode 3. According to the results, the stress-strain curve of the steel is modiied by temperature by a change in the scale of the ordinate axis. In the framework of some formulations of the weakest link model, this implies that temperature influences cleavage fracture through the yield strength of the material, and consequently the fracture toughness of the steel could be predicted as a function of temperature from the curve yield strength-temperature. The results of the fracture tests are used for assessing the accuracy of this conclusion.

THEORETICAL BACKGROUND

The weakest leak model for cleavage fracture assumes the existence of microstructural initiation sites (initiators) that becomes microcracks under plastic deformation. This would be the first step of cleavage. The propagation of these microcracks to the surrounding grains would be the second step and would produce cleavage [3]. According to [3], initiators transform into microcraks that behave as Griffith's cracks subjected to the macroscopic field of the maximum principal stress, and whose size distribution yields a probability of propagation under a maximum principal stress σ_I given by:

$$P_p = \left(\frac{\sigma_I}{s_u}\right)^m \tag{1}$$

m and s_u being material constants independent of temperature. If the initiation sites are Poisson distributed within the material [8] with an average density N, it follows that in an elementary volume dV there is no probability of having more than one, the probability of having one is NdV, and that of having none is $1-NdV$. So, the probability of finding a critical microcrack in an elementary volume dV is $NP_p dV$, where P_p must be particularized for the value of the stress field σ_I at the position occupied by dV.

Cleavage may occur in a volume $V+dV$ of plastified material because it occurs in the region of volume V, or because there is no critical microcrack in this region but one in that of volume dV. Consequently, the probability P_F of cleavage as a function of the volume V of plastified material verifies:

$$P_F(V+dV) = P_F(V) + [1-P_F(V)]NP_p dV \tag{2}$$

After some rearrangement, this equation can be integrated with the condition $P_F(0)=0$ to yield:

$$P_F(V)=1-e^{-N\int_V P_p dV}=1-e^{-Ns_u^{-m}\int_V \sigma_I^m dV} \tag{3}$$

In a cracked plate the occurrence of cleavage has no significant probability outside the fracture process zone, a region ahead of the crack tip that extends transversally through the whole thickness of the plate, *B*. When the stresses of this region are dominated by the J integral, dimensional analysis shows that the field of maximum principal stress σ_I is determined by a function $f(\bullet)$ of the form:

$$\sigma_I=R_{p0.2}\, f\left(\frac{rER_{p0.2}}{K^2},\theta\right) \tag{4}$$

where the value of the J integral is expressed in terms of a stress intensity factor *K*, *E* is the elastic modulus *E*, $R_{p0.2}$ the 0.2% yield strength, and *r* and θ are cylindrical coordinates in a system with the crack tip as axis and the crack plane as origin of the angle θ. The function $f(\bullet)$ depends on the non dimensional elastoplastic characteristics of the material, but in the case of steels these are the ones given by the stress-strain curve since the Poisson's coefficient hardly varies from one steel to another. Therefore, $f(\bullet)$ will be unique for all the steels whose stress-strain curve becomes the same as $R_{p0.2}$ used as unit stress. Eq. 3 can be particularized for the fracture process zone by means of the inverse function of $f(\bullet)$ in its first argument, $f^{-1}(\bullet)$. Let *x* be the ratio of the stresses σ_I and $R_{p0.2}$; then from Eq. 4 it follows that:

$$r=\frac{K^2}{ER_{p0.2}}\, f^{-1}\left(\frac{\sigma_I}{R_{p0.2}},\theta\right)=\frac{K^2}{ER_{p0.2}}\, f^{-1}(x,\theta) \tag{5}$$

and the integral of Eq 3 becomes:

$$\int_V \sigma_I^m dV=\int_V \sigma_I^m Brdrd\theta=R_{p0.2}^{m-2}\frac{K^4}{E^2}B\int_A x^m f^{-1}(x,\theta)\frac{\partial f^{-1}}{\partial x}dxd\theta \tag{6}$$

A being the region of the plane (x,θ) that represents the area occupied by the fracture process zone in the plate plane. When this zone is identified with the loci $\sigma_I\geq 2R_{p0.2}$ [9], the region *A* is that defined by the conditions $x\geq 2$, $-\pi\leq\theta\leq\pi$, since the contours of constant maximum principal stress in the plate plane are closed curves around the crack tip. As a consequence, Eq. 6 transforms into:

$$\int_V \sigma_I^m dV=R_{p0.2}^{m-2}\frac{K^4}{E^2}B\int_{x\geq 2} x^m\left(\int_{-\pi}^{\pi} f^{-1}(x,\theta)\frac{\partial f^{-1}}{\partial x}d\theta\right)dx=R_{p0.2}^{m-2}\frac{K^4}{E^2}BC \tag{7}$$

where the constant *C* is determined by the function $f(\bullet)$ and the exponent *m*. The substitution of Eq 7 into Eq 3 provides the probability of the plate failing by cleavage for the value of the J integral defined by *K*, or equivalently, the probability P_F of fracture toughness being less than or equal to K. Therefore:

$$-ln(1-P_F)= Ns_u^{-m}\int_V \sigma_I^m dV = NCs_u^{-m}R_{p0.2}^{m-2}B\frac{K^4}{E^2} \qquad (8)$$

As already mentioned, this theoretical result must be modified to incorporate a threshold toughness K_m independent of temperature and plate thickness. Further, if an arbitrary reference thickness B_0 and the steel grade $\overline{R}_{p0.2}$ (460 MPa for S460 N steel) are introduced, the resulting probability function of fracture toughness can be formulated in terms of a new non dimensional constant α:

$$-ln(1-P_F)= NCs_u^{-m}R_{p0.2}^{m-2}B\frac{(K-K_m)^4}{E^2}=\frac{B}{B_0}\left(\frac{K-K_m}{\alpha K_m}\right)^4\left(\frac{R_{p0.2}}{\overline{R}_{p0.2}}\right)^{m-2} \qquad (9)$$

Eq. 9 explicitly shows the influence of thickness B on fracture toughness. The yield strength $R_{p0.2}$ and the constant α incorporate that of temperature, but this last only occurs when temperature modifies the function $f(\bullet)$ by changing the shape of the stress-strain curve as previously indicated. If not, the effect of temperature on fracture toughness is that transmitted by yield strength.

In the method of the master curve for ferritic steels [6, 7], the effect of temperature on the scale parameter of the truncated Weibull distribution of Eq. 9 is assumed to depend on temperature T through a material constant T_0 incorporated into a universal function:

$$-ln(1-P_F)=\frac{B}{B_0}\left(\frac{K-K_m}{K_u+K_v e^{c(T-T_0)}}\right)^4 ln2 \qquad (10)$$

with $K_m = 20\, MPam^{1/2}$, $K_u = 0.5K_m$, $K_v = 3.5K_m$, $c = 0.019\ (°C)^{-1}$, $B_0 = 25\, mm$.

With the method of reference [10] the constant T_0 can be found from the entire set data of a fracture test series involving different temperatures and thicknesses. This method is based upon the maximum likelihood concept and does not disregard the results of the tests where ductile tearing initiation or J dominance ending precede cleavage. These can be added as randomly censored data to the random set data provided by the tests where fracture occurs by cleavage under J dominance. According to [11], for a set data consisting of n fracture toughness values K_i respectively measured being the test temperature T_i and the specimen thickness B_i, T_0 is the solution of the equation:

$$\sum_{i=1}^{i=n}\frac{\delta_i e^{c(T_i-T_0)}}{K_u+K_v e^{c(T_i-T_0)}}=\sum_{i=1}^{i=n}\frac{\hat{K}_i^4 e^{c(T_i-T_0)}}{\left(K_u+K_v e^{c(T_i-T_0)}\right)^5} \qquad \hat{K}_i=(K_i-K_m)\left(\frac{B_i}{B_0}\right)^{\frac{1}{4}} \qquad (11)$$

where δ_i is equal to 1 when K_i is an uncensored data, and to 0 if not.

EXPERIMENTAL DATA

The tensile and fracture test data of an S460N EN 10113 type structural steel were examined in relation to Eq. 10 and Eq. 9, both with the same threshold toughness $K_m = 20\,MPam^{1/2}$ and reference thickness $B_0 = 25\,mm$. Further results concerning tensile and fracture behaviour of the same steel were reported elsewhere [12]. The steel was supplied in three different plate thicknesses, 15, 30 and 50 mm.

Tensile tests were performed on the three plates, in the rolling direction, at temperatures of –30°C, 0°C and 50°C. Three or four tests were carried out per each temperature and plate thickness, the complete stress-strain curve being registered. The 0.2% yield strength was fitted as a linear function of temperature with the results given in Table 1.

TABLE 1: Yield Strength of the tested S460N steel

Thickness Plate	Yield Strength (T in °C)	T_0
20 mm	$R_{p0.2} = \overline{R}_{p0.2}(1.0563\text{-}7.27\times10^{-4}T)$	–77°C
30 mm	$R_{p0.2} = \overline{R}_{p0.2}(1.0686\text{-}7.12\times10^{-4}T)$	–60°C
50 mm	$R_{p0.2} = \overline{R}_{p0.2}(1.0365\text{-}5.90\times10^{-4}T)$	–52.5°C

Fig. 1 shows the scattering band of all the curves when plotted with the stresses referred to the 0.2% yield strength.

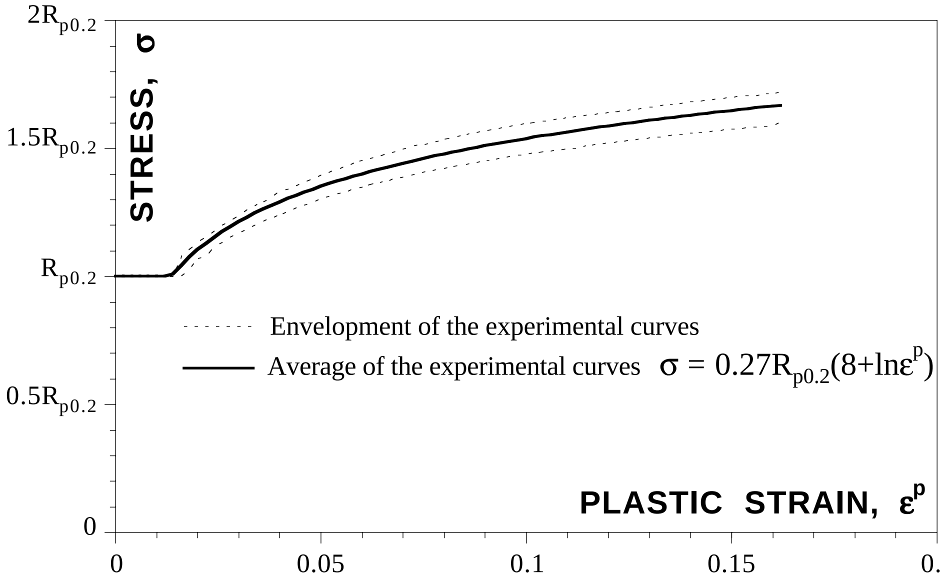

Figure 1: Scattering band of the stress-strain curves of the S460N steel for the plate thickness and temperature ranges covered by the tensile tests.

The maximum scatter is less than 4% of the average value and the deviations cannot be attributed to thickness or temperature effects, since they were indiscriminately observed between curves from tests in the same and in different test conditions. Consequently, in the explored ranges of plate thickness and temperature, the tested steel satisfies the condition to transmit the effect of temperature on fracture toughness through yield strength.

Fracture tests according to EFAM GTP 94 Standard [5] were performed by using fatigue precracked compact tensile specimens. Fatigue precracking was carried out up to a crack size 0.6 times the specimen width. Side-grooves involving a total reduction of 20% of the gross thickness were machined after precracking. The crack mouth opening displacement at the load line was measured with a COD clip gauge and registered as a function of load. The respective specimen thicknesses of the plates 20, 30 and 50 mm thick were 15, 30 and 45 mm. The width specimen was twice the thickness in the two thicker plates and 60 mm in the thinner one. The obtained toughness data are plotted in Fig. 2 as a function of temperature and thickness. The censored data are marked with the symbol ↑. All were due to the occurrence of fracture beyond the range of J dominance. The corresponding fracture toughness values are the limit of J dominance as stated by the standard. Table 1 gives the values of the temperature T_0 of the master curve found by solving Eq. 11.

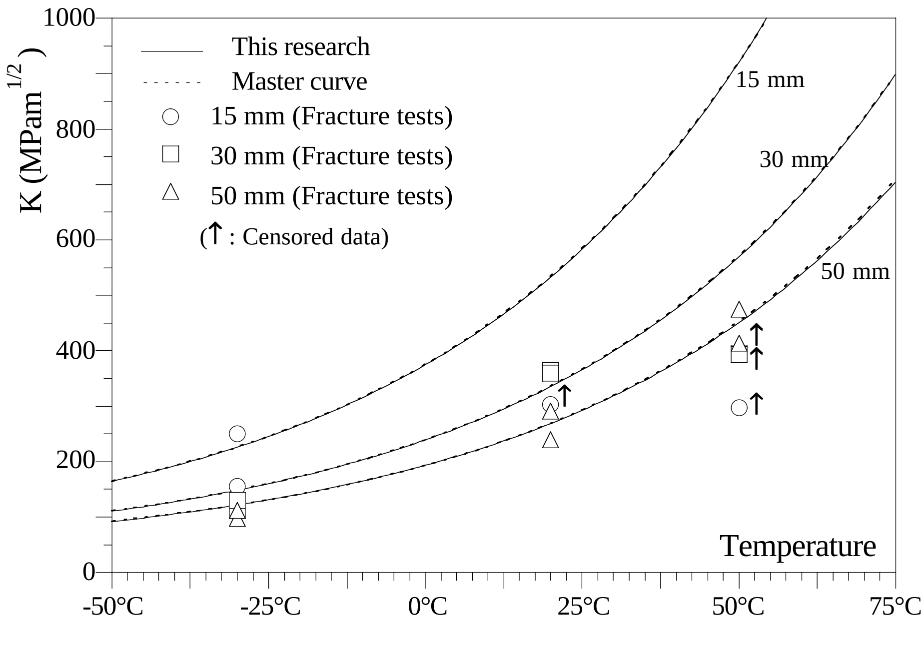

Figure 2: Experimental and theoretical fracture toughness values of the tested S460N steel.

DISCUSSION

The identification of Eq. 9 and 10 yields:

$$\frac{R_{p0.2}}{\overline{R}_{p0.2}}=\left(\frac{2(ln2)^{0.25}\alpha}{1+7e^{c(T-T_0)}}\right)^{\frac{4}{m-2}} \qquad (12)$$

where the amount α can depend on temperature according to the theory, but this does not happen in the case of the three steel plates tested as previously stated. So the linear relationships of Table 1 must coincide with the right hand member of Eq. 12 for the respective values of T_0 given in Table 1 and for appropriate values of m and α. For a given temperature range, such as that adopted in this research, the determination of the optimum values of m and α only requires a linear fit. The resulting values are given in Table 2 and are used in Fig. 2 to plot Eq. 9 particularized for $P_F = 0.5$ (the median of the population of the fracture toughness values). The analogous curves derived from Eq. 10 with the values of T_0 given by Table 1 are also plotted in Fig. 2. The two types of curves are so closely superimposed that they are practically indistinguishable.

TABLE 2: Material constants of the tested S460N steel

Thickness Plate	*20 mm*	*30 mm*	*50 mm*
m	*108*	*110*	*128*
α	*36.7*	*38.0*	*17.0*

Another fact worthy of mention regarding Fig 2 is the agreement between the experimental fracture toughness values and the median of the distribution given by Eq. 10.

CONCLUDING REMARKS

Fracture testing of an S460N steel type of Eurocode 3 has shown that the cleavage fracture of the steel agrees with the weakest link model and the master curve regarding the effect of thickness and temperature on fracture toughness. Further, it is shown that the tensile behaviour of the steel satisfies the condition for the effect of temperature on fracture toughness to be transmitted by yield strength. This is verified by the experimental fracture data.

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