DUCTILE CRACK GROWTH
IN STRUCTURAL STEELS OF EUROCODE 3

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ABSTRACT

This work examines the ductile fracture of two high strength structural steels, the SN460N and S460NL EN 10113 types. These are recommended by Eurocode 3 for the steel structures of civil engineering, where ductility is a capital requirement. The fracture behaviour of the two steels in the ductile regime is experimentally determined by means of fracture tests, considering also the effects of temperature, plate thickness and specimen size. The experimental data are analyzed to show that ductile crack growth in these steels can be explained on the basis of a single material constant whose meaning is a critical value of the crack opening angle (COA).

INTRODUCTION

Perhaps the most typical feature of the steel structures of civil engineering is their high damage tolerance which is due to the ductility of the structural steels, providing a safety margin for the structures in which the risk of catastrophic failure is low, even in seriously damaged structures. Consequently, the classical stress analyses, disregarding the existence of flaws, have long been considered in sufficient design. However, the modern codes of civil engineering are adding design rules based on Fracture Mechanics to assure the structural integrity of steel structures. Following this trend, Eurocode 3 [1] has adopted the failure assessment diagram of the R6 method, option 2 [2] to prevent fractures in a wide range of temperature, plate thickness, and strain rate. A rough description of the resulting failure criterion would be an engineering interpolation between the extreme cases of brittle fracture and plastic collapse, the latter being based on the 0.2% yield strength, $R_{p0.2}$. In this approach the ductile tearing resistance of steel is not taken into account.

This work examines the ductile tearing of two high strength structural steels recommended by Eurocode 3, of medium and high toughness. Firstly, the fracture tests performed to provide the experimental data for the analysis are described. In accordance with the plastic behaviour model assumed by Eurocode 3 for these steels, the subsequent analysis of the ductile crack growth is carried out on the basis of a plastic collapse mechanism for the tensile compact specimens used in the tests. This mechanism can be updated as a function of the growing size of the crack, so it provides a theoretical relationship between the experimental values measured during the tests (load, crack mouth opening displacement and crack size) and the analytical values involved in the available fracture criteria for extended crack growth. The appropriate criterion for the examined steel is identified and the ductile tearing resistance is measured in terms of a single material constant, which provides a quantitative support to evaluate the influence of temperature and plate thickness on the ductile tearing resistance of the steel.

MATERIALS AND EXPERIMENTAL PROCEDURE

Analyses were made of the S460N and a S460NL EN 10113 [3] types structural steels. These weldable fine grain steels are normalized/normalized hot rolled products. The first was supplied in three different plate thicknesses, 20, 30 and 50 mm, and the second in four plate thicknesses, 20, 30, 50 and 80 mm. The mechanical test programme included tensile and fracture tests. Table 1 gives the chemical composition of the steels as determined from the final product. The results meet the requirements of EN 10113 for normalized/normalized rolled steels and confirm the presence of alloying elements (Ni, Al, V, Nb) used for grain refinement and transformation control.

TABLE 1

CHEMICAL COMPOSITION OF THE TESTED STEELS

	% C	% Si	% Mn	% P	% N	% S	% Al	%Ni	% Nb	% Cu	% Cr	% Mo
Steel 460N	0.18	0.41	1.54	0.015	–	0.002	0.071	0.47	0.057	–	–	0.143
Steel 460 NL	0.07	0.38	1.57	0.012	0.005	0.001	0.043	0.42	0.02	0.16	0.025	0.14

Tensile tests were performed on the seven plates at two temperatures of the ductile regime: 20°C and 50°C. The tensile specimens were machined longitudinally, in the rolling direction and centered in the plate thickness. The stress-strain curve of the steel at the test temperature was recorded up to fracture. In all the cases yielding occurs at essentially constant stress, but after yielding the steel strain hardens significantly. The mechanical properties (0.2% yield strength, tensile strength, maximum load elongation and ultimate elongation) are given in Tables 2 and 3 as a function of plate thickness and temperature. The room temperature properties required by EN 10113 for S460N and S460NL steel types are fulfilled by the seven steel plates.

TABLE 2

TENSILE PROPERTIES OF THE TESTED S460N STEEL

		Plate thickness		
	Temperature	20 mm	30 mm	50 mm
Young´s modulus E	20°C 50°C	195 GPa 185 GPa	200 GPa 185 GPa	200 GPa 195 GPa
0.2 % Yield stress $R_{p0.2}$	20°C 50°C	485 MPa 460 MPa	490 MPa 470 MPa	475 MPa 460 MPa
Ultimate tensile strength R_m	20°C 50°C	680 MPa 640 MPa	690 MPa 660 MPa	665 MPa 640 MPa
Maximum uniform elongation ε_u	20°C 50°C	16.5 % 13.0 %	9. 0 % 10.0 %	16.0 % 15.0 %

Fracture tests based on EFAM GTP 94 Standard [4] were performed by using fatigue precracked compact tensile specimens with side-grooves involving a total reduction of 20% of the gross thickness. Fatigue pre-cracking was carried out according to the standard up to a crack size 0.6 times the specimen width. The side-grooves were machined after precracking. Apart from the applied load, the crack mouth opening displacement at the load line was measured and continuously registered by means of a COD clip gauge. All the specimens failed by ductile tearing. The crack growth produced throughout the test was determined from the elastic compliance, measured at the load line by periodical partial unloadings. The specimen dimensions (the thickness B and width W) are given in Tables 4 and 5 together with the whole crack growth produced during the test, •a_{max}.

TABLE 3

TENSILE PROPERTIES OF THE TESTED S460NL STEEL

	Temperature	Thickness plate			
		20 mm	30 mm	50 mm	80 mm
Young´s modulus E	20°C 50°C	200 GPa 205 GPa	205 GPa 190 GPa	210 GPa 215 GPa	190 GPa 200 GPa
0.2 % Yield stress $R_{p0.2}$	20°C 50°C	450 MPa 440 MPa	490 MPa 470 MPa	455 MPa 470 MPa	430 MPa 410 MPa
Ultimate tensile strength R_m	20°C 50°C	545 MPa 525 MPa	595 MPa 575 MPa	555 MPa 540 MPa	540 MPa 515 MPa
Maximum uniform elongation ε_u	20°C 50°C	12.0 % 13.6 %	10. 3 % 12.0 %	14.9 % 14.5 %	11.2 % 13.0 %

TABLE 4

FRACTURE TESTS PERFORMED IN STEEL S460N

Plate Thickness	Test Temperature	Specimen dimensions		Crack growth •a_{max}
		Thickness B	Width W	
20 mm	20°C	15 mm	60 mm	3.0 mm
	50°C	15 mm	60 mm	3.5 mm
30 mm	50°C	30 mm	60 mm	3.5 mm
50 mm	50°C	45 mm	90 mm	3.0 mm

TABLE 5

FRACTURE TESTS PERFORMED IN STEEL S460NL

Plate Thickness	Test Temperature	Specimen dimensions		Crack growth •a_{max}
		Thickness B	Width W	
20 mm	20°C	20 mm	60 mm	2.6 mm
30 mm	20°C	30 mm	60 mm	2.0 mm
50 mm	20°C	45 mm	90 mm	3.5 mm
80 mm	20°C	30 mm	60 mm	3.4 mm
		45 mm	90 mm	3.2 mm
		75 mm	150 mm	6.0 mm
	50°C	75 mm	150 mm	4.5 mm

THEORETICAL FORMULATION

The steel types of Eurocode 3 yield at constant stress, so this code assumes plastic collapse as condition for ductile failure. Accordingly, the collapse mechanism shown in Fig. 1 is assumed for the tested compact tensile specimens. The slip line field involved in this mechanism, proposed by Ming Hu and Albretch [5], consists of a stress constant triangular region bounded by the back face of the specimen and by two isolated slip lines separating rigid regions. The stress constant region is a rectangular isosceles triangle. The prolongation of each one of its equal sides is a part of one of the two isolated slip lines, the other being a circular curve that ends at the crack tip. This slip line field divides the compact specimen into two rigid symmetric halves separated by the yielded material of the stress constant triangle and by the rigid material enclosed by the two isolated slip lines. Therefore, when the specimen is pulled, a velocity field develops such that each rigid half of the specimen instantaneously rotates around the center of its circular boundary causing the yielded triangle to move outside.

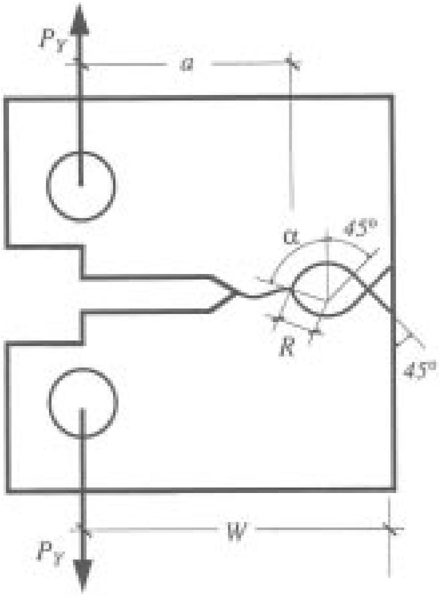

Figure 1.– Collapse mechanism for the tensile compact specimen.

The equilibrium between external and internal forces allows the values of the angle α, the radius R and the failure load P_Y to be derived [5]. For a specimen of net thickness B and rigid-perfectly plastic material with yield strength σ_Y, this gives:

$$\alpha = 72^\circ \tag{1}$$

$$\frac{R}{W} = \sqrt{0.6977\left(\frac{a}{W}\right)^2 + 0.409} - 1.052\frac{a}{W} \tag{2}$$

$$P_Y = \sigma_Y WB\left[2.481\sqrt{\left(\frac{a}{W}\right)^2 + 0.586} - 1.970\frac{a}{W} - 1.155\right] \tag{3}$$

Most of the fracture criteria for growing cracks state that the crack profile near the crack tip must be the same regardless of the crack size. The local slope of the crack faces is a representative measurement of this profile and can be estimated from the crack opening angle (COA), defined as the ratio of the crack opening displacement at the site of the initial crack tip, δ, to the current crack extension, •a [7].

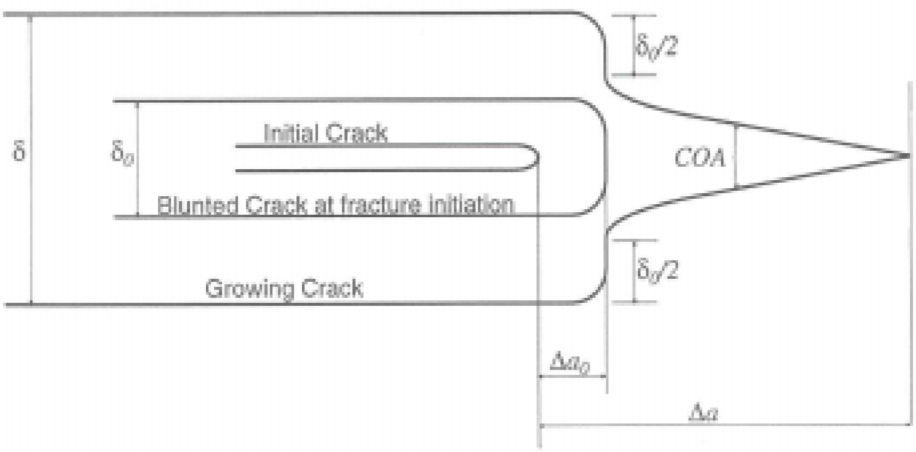

Figure 2.– The Crack Opening Angle (COA).

Once the effects of the crack blunting on Δa and δ are discounted (Fig. 2), the resulting expression for the COA is:

$$COA = \frac{\delta - \delta_0}{\Delta a - \Delta a_0} \tag{4}$$

For a compact tensile specimen being deformed as shown in Fig 1, the COA can be derived as a function of Δa and the displacement u_{pc}. The relationship between the displacement velocities $\dot{u}_{pc}$ and $\dot{\delta}_{pc}$ is determined by the angular velocity ω at which each rigid half of the specimen rotates (see Fig. 3):

$$\left.\begin{aligned} \dot{\delta}_{pc} &= 2\dot{\theta}(\Delta a + R\sin 72°) \\ \dot{u}_{pc} &= 2\dot{\theta}(a_0 + \Delta a + R\sin 72°) \end{aligned}\right\} \Rightarrow \dot{\delta}_{pc} = \frac{\Delta a + R\sin 72°}{a_0 + \Delta a + R\sin 72°}\dot{u}_{pc} \tag{6}$$

and hence:

$$COA = \frac{\delta_{pc} - \delta_0}{\Delta a - \Delta a_0} = \frac{1}{\Delta a - \Delta a_0}\int_{\delta_0}^{\delta_{pc}} d\delta_{pc} = \frac{1}{\Delta a - \Delta a_0}\int_{u_0}^{u_{pc}} \frac{\Delta a + R\sin 72°}{a_0 + \Delta a + R\sin 72°}\, du_{pc} \tag{7}$$

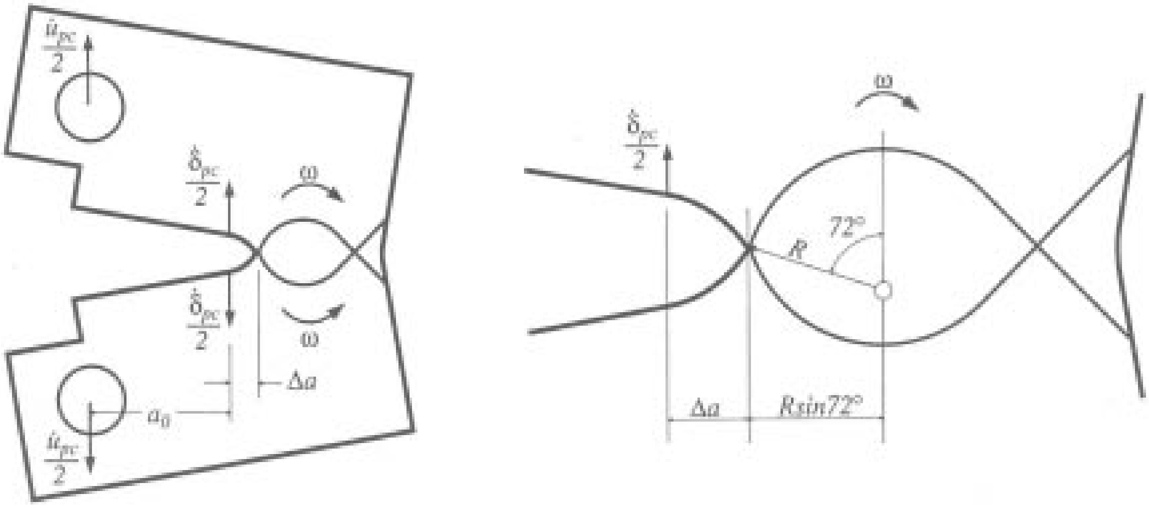

Figure 3.– Displacement velocities in the tensile compact specimen.

For the crack extension values of Table 3, the ratio a/W and the function in the integral of Eq (8) respectively range from 0.6 to 0.64 and from 0.22 to 0.24, so that the function can be taken as a constant, so Eq (8) becomes:

$$COA = \frac{R\sin 72°}{a_0 + R\sin 72°}\frac{u_{pc} - u_0}{\Delta a - \Delta a_0} \tag{8}$$

DISCUSSION

Eq (8) can be applied to the fracture test performed in this research by using the crack extension measurements made during the tests and by identifying the displacement u_{pc} of the model of Fig 1 with the plastic component u_p of the displacement u recorded in the tests. The resulting values of the COA and the corresponding scatter given in Tables 5 and 6 show that ductile tearing occurs under a constant value of the COA in the examined S460N and S460NL steels, regardless of plate thickness, temperature and specimen size. Fig 4 and Fig 5 respectively illustrate this for a test performed in each steel. The values taken as u_0 and Δa_0 to apply Eq (8) were that of u_p and Δa at fracture initiation, this event being determined as the Standard EFAM GTP 94 [4] states. The constant value of the COA for each steel agrees with their respective toughness as typified by Eurocode 3 on the basis of the required Charpy impact energy: according to these requirements, S460N steel is a medium toughness steel, whereas 460NL steel is a high toughness steel. The COA values at fracture of 460NL steel duplicates that of 460N steel, so they represent a ductile tearing resistance in acordance with the expected toughness. The influence of temperature is slight on the 460N steel plate 20 mm thick and more important on the 460NL plate 80 mm thick. In both cases the COA values at fracture indicates that the ductile tearing resistance increases with temperature. The specimen size does influence the COA value at fracture, as is shown by the tests at room temperature of the 460NL steel plate 80 mm thick. Since the ductile tearing resistance decreases with the specimen size, this size effect can be attributed to the higher stress triaxiality produced in the larger sizes. The plate thickness is known to affect tensile properties such as the yield strength [8], but its influence on toughness cannot be assessed from these experimental results because it is masked by the size effect.

TABLE 5

ANALYSIS OF THE FRACTURE TESTS IN S460N STEEL

Plate Thickness	Test Temperature	Specimen Thickness	Test Results		
			u_0	• a_0	COA Range
20 mm	20°C	15 mm	2.1 mm	1.3 mm	0.26 ± 0.04
	50°C	15 mm	2.7 mm	1.6 mm	0.29 ± 0.02
30 mm	50°C	30 mm	3.8 mm	2.6 mm	0.29 ± 0.01
50 mm	50°C	45 mm	3.3 mm	2.0 mm	0.28 ± 0.02

TABLE 6

ANALYSIS OF THE FRACTURE TESTS IN S460NL STEEL

Plate Thickness	Test Temperature	Specimen Thickness	Test Results		
			u_0	• a_0	COA Range
20 mm	20°C	20 mm	6.1 mm	1.7 mm	0.62 ± 0.07
30 mm	20°C	30 mm	4.1 mm	1.0 mm	0.75 ± 0.04
50 mm	20°C	45 mm	6.9 mm	1.8 mm	0.70 ± 0.02
80 mm	20°C	30 mm	6.0 mm	1.5 mm	0.77 ± 0.07
		45 mm	6.4 mm	1.6 mm	0.72 ± 0.03
		75 mm	5.5 mm	1.4 mm	0.63 ± 0.02
	50°C	75 mm	5.6 mm	1.2 mm	0.79 ± 0.05

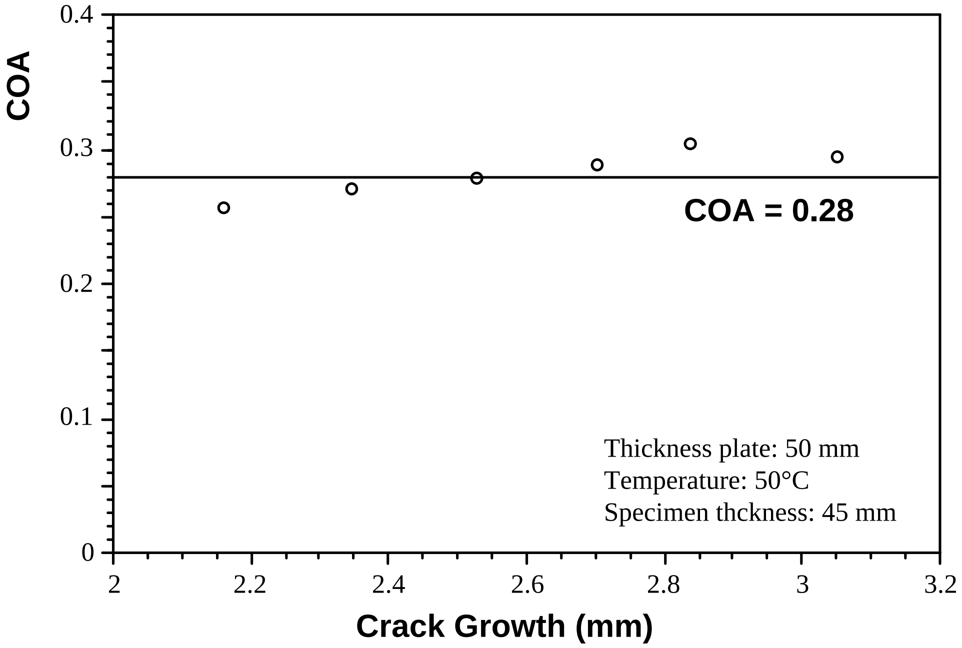

Figure 4.– Evolution of the COA values during a fracture test of 460N steel.

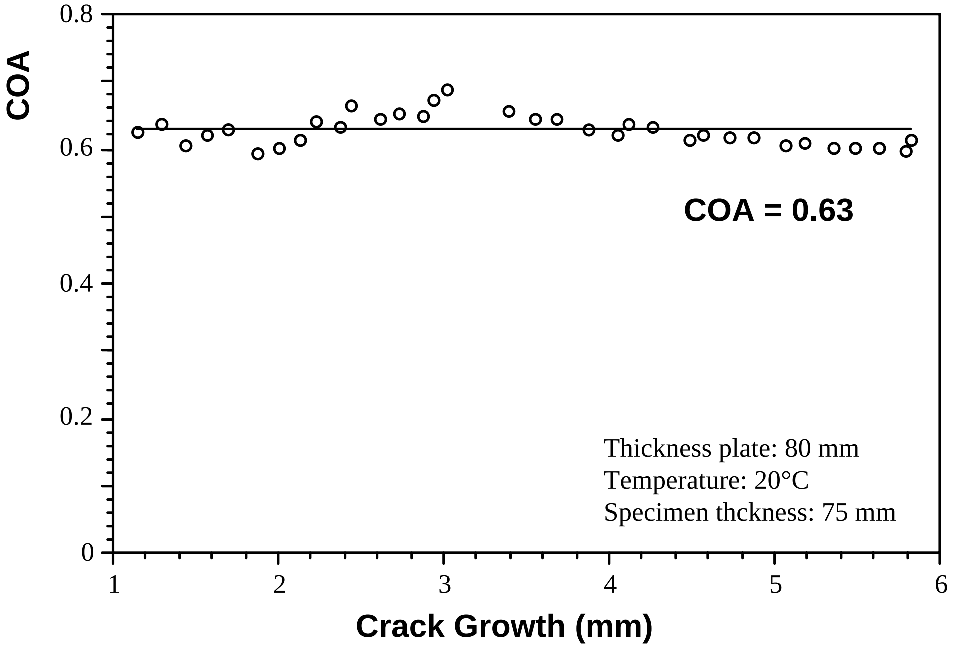

Figure 5.– Evolution of the COA values during a fracture test of 460NL steel.

CONCLUDING REMARKS

The ductile tearing of two high strength steels recommend by Eurocode 3 for steel structures is shown to obey a fracture criterion based on a critical value of the crack opening angle (COA). The ductile tearing resistance, as measured by the COA, agrees with the toughness levels assigned by Eurocode 3 and is in accordance with the expected effects of temperature and specimen size.

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