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INFLUENCE OF MATERIAL THICKNESS ON THE DUCTILE FRACTURE OF STEEL PLATES FOR SHIPBUILDING

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ABSTRACT

In the shipbuilding industry, the risk of brittle fractures is relatively high because some units operate in arctic or subarctic zones and use high thickness (up to 100 mm) steel plates in their structures. This risk is limited by employing certified materials with a specific impact strength, determined using the Charpy method (for a given design temperature) and by exercising control over the welding processes (technology qualification, production supervision, and non-destructive tests). However, for offshore constructions, such requirements may prove insufficient. For this reason, regulations employed in constructing offshore structures require conducting crack tip opening displacement (CTOD) tests for steel and welded joints with thicknesses exceeding 40 mm for high tensile strength steel and 50 mm for other steel types. Since classification codes do not accept the results of CTOD tests conducted on specimens of sub-sized dimensions, the problem of theoretically modelling the steel construction destruction process is of key importance, as laboratory tests for notched elements of considerable thickness (100 mm and higher) are costly and problems stemming from high loads and a wide range of recorded parameters are not uncommon. The aim of this research is to find a relationship between material thickness and CTOD value, by establishing and verifying a numerical model that allows recalculating a result obtained on a sub-size specimen to a full- size specimen for a ductile fracture mode. This work presents results and conclusions from numerical modelling and compares them with laboratory test results of the elastic-plastic properties of high thickness steel, typically used in offshore applications.

Keywords: ductility, toughness, plasticity, CTOD

INTRODUCTION

Ductility is used as a measure of a material's resistance to cracking. In the shipbuilding industry, the Charpy method is usually used. This test is a strictly quantitative method and is performed on small, standardised specimens, usually with the dimensions 10 x 10 x 55 mm. As a measure of a material's toughness, the energy absorbed when breaking a specimen, by striking it with a pendulum hammer into a notched specimen, is determined. The test result is satisfactory if the average absorbed energy is greater than the reference value for a given type of steel at a particular temperature. Although it has some advantages, like price and time required to perform the test, the Charpy method presents several disadvantages: the specimen has a standardised size which is independent of thickness, the test results only deliver a number without any information about the failure mode, the notch in the test specimen is cut mechanically and its geometry depends on the shape of the cutter used (which changes with time and produces different notch shapes). For this reason, alternative methods were investigated to assess material ductility.

In the early 1920s a new branch of science came into being: fracture mechanics. Depending on fracture type, three main parameters were introduced (Fig. 1):

- Stress intensity factor (SIF), denoted as K, was proposed by Griffith [1] for the brittle fracture mode.
- Crack Tip Opening Displacement (CTOD), was proposed by Wells [2] for the mixed (ductile and brittle) fracture mode.
- J-integral, proposed by Rice [3], for the ductile fracture mode. J-integral can also be used for elastic analysis of the stress intensity factor.

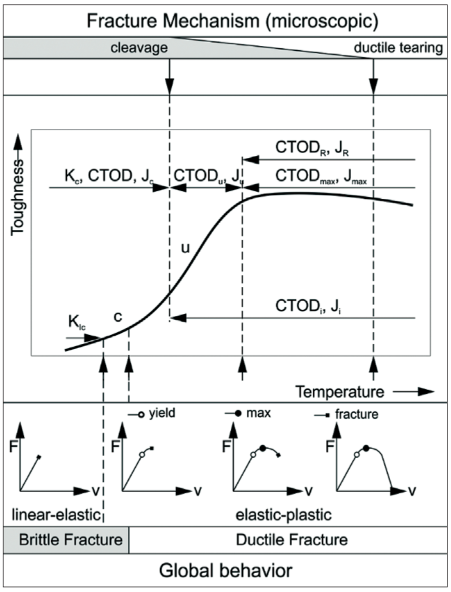

Fig. 1. Fracture mechanics factors and their applicability to fracture process descriptions [4]

This paper focused on CTOD, due to the fact that this factor is required by classification societies standards [5-8]. The fundamentals of the CTOD test are based on breaking a specimen with a full thickness of the material, subject to verification. The specimen has a preliminary, mechanically cut notch, which then develops (through fatigue processes) to such a size that the effects of mechanical treatment stay far from the front of the fatigue notch and the shape of the notch front is repeatable for each specimen. To check this repeatability, the results of the test are verified after the specimen is fully fractured and only accepted if the proportion of the fatigue fracture front is properly verified. There are a few types of specimens defined in the standards [9-11], which differ in terms of shape, type of loading and, different stress states in front of the crack tip. The most commonly used are: compact specimens (straight-notch and stepped-notch), which are in tension and bending at the same time, bending specimens with a single notch SNE(B), and tension specimens with a single edge notch SNE(T). The dimensions of the specimens depend on the thickness of the material to be tested and the specimen type. The CTOD values obtained for different specimen types vary. Results obtained for SNE(B) specimens are more conservative compared with SEN(T) specimens [12]. Current rules for shipbuilding [5-8] require CTOD tests on SEN(B) specimens with a recommended section geometry B x W (W=2B), where B is the thickness of the material, see Fig. 2. The principle of the CTOD test for a ductile material and bent specimen is shown in Fig. 2.

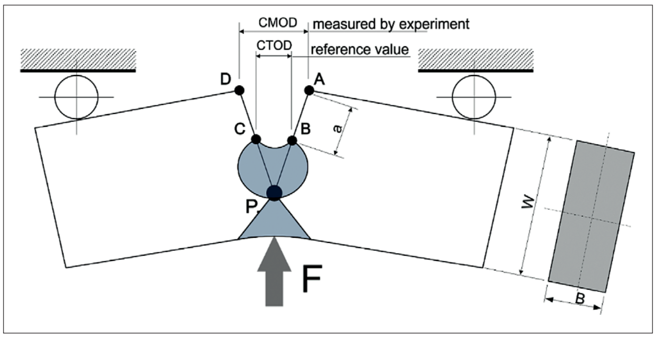

Fig. 2. Principle of the CTOD test

CTOD is a geometric value that can be defined as follows.

$$\delta_T = \frac{r_y(W-a)AD}{r_y(W-a)+a} = \frac{r_y(W-a)\delta_M}{r_y(W-a)+a} \tag{1}$$

where r_y is a coefficient:

$$r_y = \frac{CBa}{(W-a)(AD-CB)} \tag{2}$$

Coefficient r_y usually takes values in the range 0.38–0.46 [13]. The effect of stable tearing (crack extension), which is characteristic of ductile fractures, is not included in Eq. (1) for CTOD calculations.

The equations for CTOD evaluation, which were introduced into the standards [9–11], are still being improved. The equations in [9], for the SNE(B) specimen type (see Eq. (3)) are based on the geometry of the specimen, relative crack length, plastic component of CMOD (see Fig. 2) and the maximum value of force. A different approach is presented in ASTM [10] and ISO [11], where an energy-based concept is the basis for CTOD evaluation. Recent research by Kawabata et al. [14] and Khor [15] resulted in modification of the CTOD formulas in the ISO 12135 standard, 2021 edition.

The requirement that specimen thickness B should be equal to (or almost equal, due to technological issues connected with specimen preparation) the tested material's thickness, in the case of thick materials, causes problems. As has been mentioned before, specimen dimensions depend on the material's thickness. For example, for 100 mm thick material (specimen type SNE(B)), the recommended specimen geometry (B x 2B) dimensions will be equal to: length 920 mm x breadth 100 mm x width 200 mm, and the mass of the specimen will be approximately 145 kg. Such a specimen requires strength machines with high load capacities and it is very difficult to operate this during the testing procedure. This is the reason why the investigation of the influence of specimen size on CTOD test results has been performed. Some authors have pointed out that the toughness value of materials is influenced by factors like specimen size and thickness, loading rate and crack depth. These factors influence both the toughness value and the transition temperature, see Fig. 3 [16].

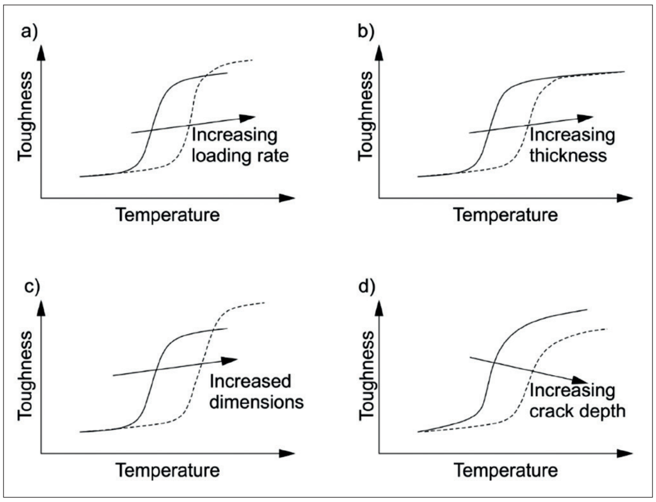

Fig. 3. Effect of loading rate (a), thickness (b), specimen dimension (c) and crack depth (d) on ductile-to-brittle transition curves [16]

Gough [17] proposed that CTOD and J values increase with specimen size (based on laboratory test results). Palombo, Sandon and Marco [18] showed that CTOD increases with specimen size but decreases with temperature (Fig. 3c). Kowalski and Kozak [19] investigated and described the influence of crack depth, as a linear function (Fig. 3d), on CTOD value. Kowalski [20] showed differences in the influence of specimen thickness and notch depth on CTOD value.

These examples show that the problem has been discussed, mainly qualitatively. In this paper, we attempt to quantify the influence of specimen size on the CTOD value for steel, based on numerical calculations, which model material behaviour in the ductile failure process, and verified by natural scale laboratory test results.

RESEARCH METHODOLOGY

The idea of this research was to study the influence of material thickness on toughness (see Fig. 2c). The test was carried out according to the standards for the CTOD test [9, 11], based on three-point bending specimens SNE(B). The test was planned assuming a changing specimen width, with constant geometrical proportions and keeping a_0/W (where a0 is an initial crack length) constant and equal to 0.60. Three specimens were tested for each thickness. The geometry and masses of the tested specimens are presented in Fig. 4. Specimens were denoted as W60, W80, W100, and W120, where the number is a height of the specimen in mm.

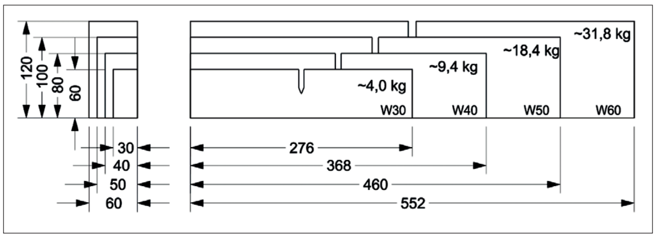

Fig.4. Dimension and mass of the specimen

All specimens (including specimens for tensile testing) were cut from one plate made of NV E36 DNV PT.2 CH2 SEC.1:2016 high tensile steel for shipbuilding, with the mechanical properties presented in Table 1 and the chemical composition given in Table 2.

Tab. 1. Material properties of tested steel

Tensile test result			
Yield point, R_e [N/mm²]	Ultimate strength, R_m [N/mm²]	Elongation, A_{50} [%]	Elastic modulus, E [GPa]
398	537	29	215

Impact test result, size 10 x 10 x 55, type KV, Longitudinal [J]				
	1	2	3	4
temp +20°C	146	133	121	133
temp -40°C	210	202	209	207

Tab. 2. Chemical composite of tested steel

C	Si	Mn	P	S	Al	Nb
0.161	0.46	1.50	0.012	0.002	0.031	0.042
V	Ti	Cu	Cr	Ni	Mo	Ca
0.052	0.005	0.016	0.50	0.040	0.006	0.002

Mechanical properties were determined by in-house testing on an upgraded ZD-40 Pu machine (force measurement accuracy ±1% of the measured value). Elongation was measured using an Epsilon 2543-050M-025M-ST extensometer with a 50 mm measuring base. The extensometer allowed measurement up to the point of specimen rupture with an accuracy of ±0.001 mm. Specimens with a circular cross-section, 10 ±0.1 mm in diameter, were used for the test. The specimen was tested under tensile stress at a strain rate $\dot{\varepsilon}$= 0.0044 1/s. The tensile curve is presented in Fig. 5.

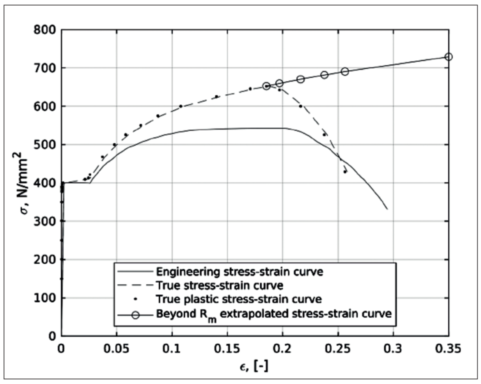

Fig. 5. Tensile testing results expressed in the form of engineering and true stresses

NUMERICAL ANALYSIS

The aim of the modelling was to find the relationship between specimen thickness and CTOD value. Due to the double symmetry of the specimens, a quarter of the volume and corresponding supports were modelled. The simplification of assuming no friction between the supports and the specimen was employed in the process. True stress – strain plastic curve, extrapolated beyond R_m was used. The material model containing ductile damage mechanisms, based on strain and stress triaxiality, was also used. A time-domain simulation was conducted using an explicit method. A standardised, physical CTOD test was performed in the displacement control mode. The same situation took place for numerical simulation.

The problem was modelled with Abaqus CAE software. The mesh size in critical regions was 0.5 mm for all models, which was a good compromise between result quality and computation time. In the neighbourhood of the crack, a C3D8R element was applied. For the biggest specimen, changing the mesh size in the critical region to 0.25 mm made the recalculated CTOD result different by -3.6%, in comparison to a mesh size of 0.5 mm. Force vs. CMOD (Crack Mouth Opening Displacement) plots for different element sizes are presented in Fig 6. Significant results of mesh convergence analysis are presented in Table 3.

Tab. 3. Summary of element size study

Element size in crack tip region, [mm]	F_m, [kN]	V_p, [mm]	δ, [mm]	F_m error [%]	V_p error [%]	$δ_m$ error [%]	Normalised computation time, [-]
0.25	200.4	15.81	3.45	1.3	-4.0	-3.6	22.15
0.50	197.8	16.47	3.58	0.0	0.0	0.0	1.0
0.60	211.5	17.63	3.84	6.9	7.0	7.3	0.68
1.00	223.1	17.97	3.93	12.8	9.1	9.6	0.09

Where:

F_m – Maximum force for a test which exhibits a maximum force plateau, N;

V_p – plastic component of CMOD, mm;

δ – CTOD, calculated in accordance with Eq. (3), mm;

F_m error – F_m error in relation to the 0.5 mm element size mesh, [%].

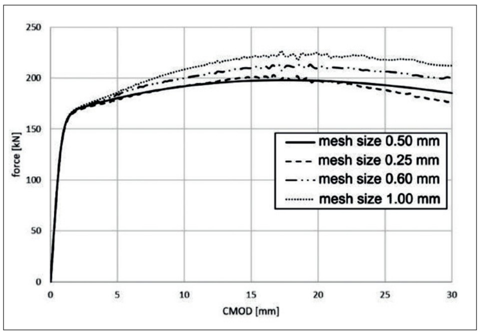

Fig. 6. Force vs. CMOD plots for various element sizes

Detailed information on modelling the material fracture description, the calibration of the model and its verification are presented in [19] and [21]. Fig. 7 presents the typical output from simulations with stress distribution along the crack.

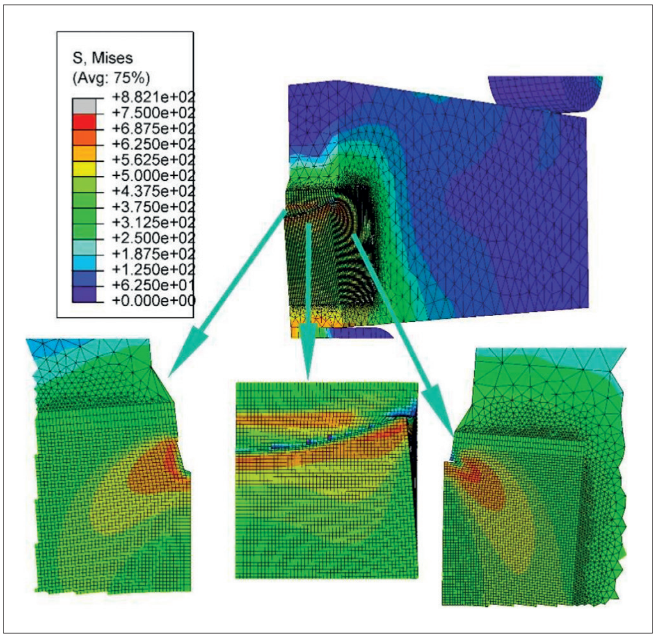

Fig. 7 Model of 3-point bending specimen with subsequent destruction

LABORATORY TESTS

The tests were performed on a dedicated stand with measurements of load, displacement and crack opening displacement (COD). Fig. 8 presents the sizes of the tested specimens (from W30 to W60). Force was measured by a 250 kN load cell with 1% accuracy. For COD measurement, an Epsilon 3541-010M-120M-LT COD gauge was used. The resolution of this gauge is 0.001 mm and the permissible error cannot exceed 0.5%. Before the CTOD test started, fatigue pre-cracks were generated into the specimen. The maximum pre-crack force for a given specimen size was calculated in accordance with (BSI 1991) and (ISO 2016). Force values calculated in accordance with BS 7448 (BSI 1991) were lower than those in accordance with ISO 12135 (ISO 2016) and so they were chosen. Calculated R (fatigue force ratio) was equal to 0.1 for each case.

The second stage (after pre-cracking) of testing CTOD was the process of breaking. Fig. 9 shows a W100 specimen on the test stand during the test.

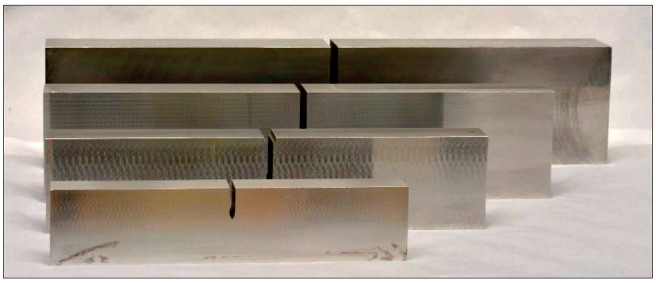

Fig. 8 Set of specimens representing the full spectrum of thicknesses applied

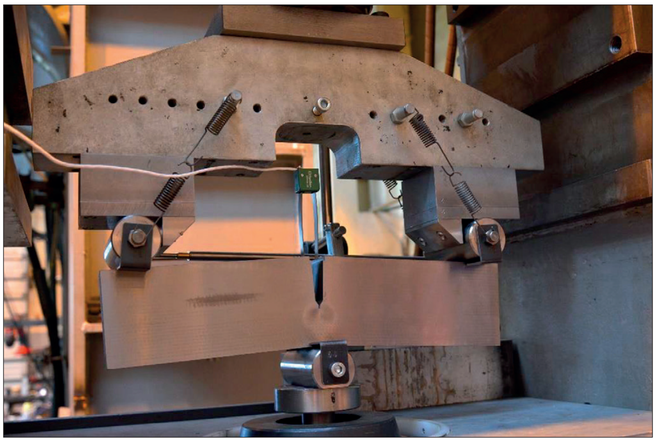

Fig. 9. W100 Specimen during laboratory testing—breaking phase

After the process of breaking, as the third stage of the test, the specimen was separated into two parts to open the cracking plane for real a_0 value measurement. We used a standard procedure and a detailed description is available in [9-11]. The final stage of quality control for the results was to check if the assumed numerical calculations from the ductile damage mechanism were appropriate for this case. For this purpose, a scanning electron microscope (SEM) investigation was performed and the results are shown in Fig. 10.

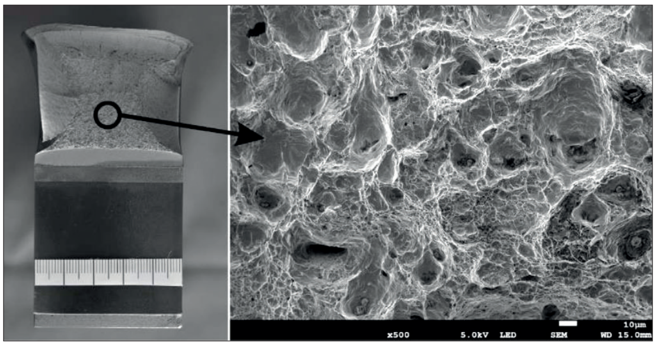

Fig. 10. SEM investigation results—ductile failure mode. Shear lips were formed during the final stage of specimen breaking—after data acquisition stopped

One can see that the failure mechanism was ductile, as was expected. Voids are clearly seen. The applied numerical failure model was phenomenologically correct.

RESULTS AND DISCUSSION

Results from both the numerical simulation and laboratory testing were processed in exactly the same way, using the CMOD vs. force records and procedure described in [9] and [11]. The following formula was used as a method for CTOD calculation for three-point bend specimens:

$$\delta_T = \left[\frac{FS}{BW^{1,5}} f\left(\frac{a_0}{W}\right)\right]^2 \frac{(1-\nu^2)}{2R_{P02}E} + \frac{0.4(W-a_0)V_p}{0.4W+0,6a_0+z} \quad (3)$$

where F is the force, N; $f(a_0/W)$ is the stress intensity factor coefficient, [-]; σ_{RP02} is the proof strength at 0.2% plastic elongation, N/mm^2; ν is the Poisson ratio for steel, ν = 0.3; [-], V_p is as defined before, mm; and z is the initial distance of the notch opening gauge measurement position from the notched edge of the specimen, z = 0, in mm.

A comparison of the test results with FEM calculation results, for a 100 mm wide specimen, is presented in Fig. 11.

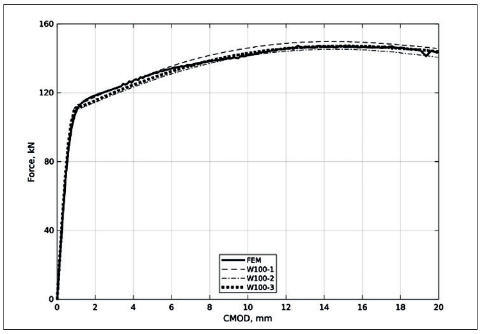

Fig. 11. Comparison of test results (W-100-1,2,3) with FEM calculation results for a specimen width of 100 mm

The results of the numerical simulation and laboratory tests are presented in Table 4 and Table 5. Both sets of results are in good agreement. The difference between FEM and average laboratory values for W60, W80, W100 and W120 are 0.0%, 1.2%, 0.7% and 4.5%, respectively. For the first three cases, the results of FE calculations and laboratory tests can be treated as being equal. The last one is noticeable because a lower value was obtained in the FE calculation; thus, the results are conservative and can be used safely.

Tab. 4. FEM results summary

Specimen	B, mm	W, mm	a0/W, [-]	δ, mm
FEM B30	30	60	0.60	2.01
FEM B40	40	80	0.60	2.55
FEM B50	50	100	0.60	3.12
FEM B60	60	120	0.60	3.58

Table 5. Laboratory test results summary

Specimen	B, mm	W, mm	a0/W, [-]	δ, mm	δ_{av}, mm
W60	29.98	60.17	0.63	1,97	2.01
	30.02	60.15	0.60	2.04	
W80	39.77	80.05	0.60	2.63	2.58
	40.02	80.17	0.60	2.52	
	40.10	80.12	0.60	2.59	
W100	59.26	100.37	0.59	3.17	3.10
	59.35	100.32	0.59	3.08	
	59.65	100.23	0.60	3.04	
W120	59.90	120.17	0.60	3.77	3.75
	60.10	119.73	0.60	3.74	
	60.10	120.08	0.60	3.74	

The test results and FEM calculations for the whole of the tested series are presented in Fig. 12.

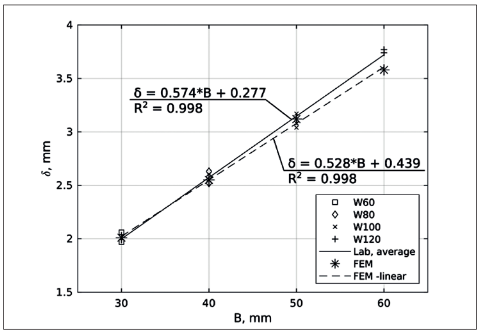

Fig. 12 Test results and FEM calculations for the whole program of tests

The results presented in Fig. 12 are almost linear in character, with a significant influence of specimen thickness on critical crack opening displacement. Linear approximations for laboratory test results, as well as FEM analysis, are presented in Fig. 12. Such equations can be used for assessing CTOD for other material thicknesses.

CONCLUSIONS

- Numerical simulations, verified by laboratory testing, prove the influence of specimen size on CTOD value. The model of plastic flow presented in this paper gave acceptably accurate results. However, future research should take into account the latest methods to define stress flow after necking.
- The results obtained by numerical modelling present an almost linear relationship between the size of the specimen and CTOD value.
- Laboratory verification tests confirmed the truth of this relationship and good numerical and experimental result compliance was obtained. Thus, the presented and properly calibrated numerical model can be used for evaluating scale effects in CTOD tests.
- The research was conducted at a constant room temperature, which means that ductile failure was assumed, for a particular steel grade with a constant a0/W ratio. Thus, the presented procedure is limited to certain test conditions.
- The next step for improving the numerical model is to verify the crack extension process during the numerical simulation. It should allow reliable evaluation of the influence of specimen size on CTOD. The problem, which is still open, is to quantify the size effect (thickness of material) on the Ductile-To-Brittle Transition Curve.

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