EVALUATION OF A FINITE ELEMENT MODEL FOR SENT TESTING OF WELDED CONNECTIONS

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Abstract: The SENT test has recently gained popularity for the characterization of the ductile tearing resistance of welded connections under low crack tip constraint. In addition to this practical purpose, Soete Laboratory adopts the SENT test as a tool to investigate effects of weld strength heterogeneity on the crack driving force response of weld defects. The numerical aspect of this investigation relies on a finite element model of a SENT specimen in which the heterogeneous strength properties of the weld region are defined on the basis of an imported hardness map. This paper evaluates the model in two respects. First, crack driving force response is validated on the basis of an experimental SENT test result of a non-welded specimen. Second, the potential effect of the transfer function between hardness and constitutive properties is illustrated. It is concluded that more work is required to improve the feasibility of weld hardness data as a means to characterize effects of weld strength heterogeneity.

Keywords: SENT test, CTOD, weld, heterogeneity

1 INTRODUCTION

Welding is a joining technique used in countless applications and industries, e.g. machine construction, pipelines, building, furniture, windmills, vehicles and vessels. Although much depends on the type of welding, the materials used and the welder skills, welds always contain flaws. When rejected by workmanship rules, flaws are categorized as defects. An engineering critical assessment (ECA) determines whether or not a defected weld can be accepted and the structure can be kept in service. An elaborate description of ECA and its development in the past is provided by Wiesner et al. [1]. Several ECA procedures exist, e.g. API1104, BS7910, FITNET FFS [2][3][4] and these are now used routinely by the oil and gas, nuclear, aerospace, petrochemical and power industries to determine the safety of their structures.

In ECA procedures, a weld is severely idealized in two ways: it is reduced to a weld with straight fusion lines and with homogeneous properties, see Figure 1. Heterogeneity within the weld and the heat affected zone (HAZ) and the irregularity of the weld fusion lines are completely ignored. The goal of this project is to implement weld heterogeneity into the ECA. Thereto a more thorough study of weld strength heterogeneity is required. In the context if this study, the feasibility of using hardness values to predict tensile strength

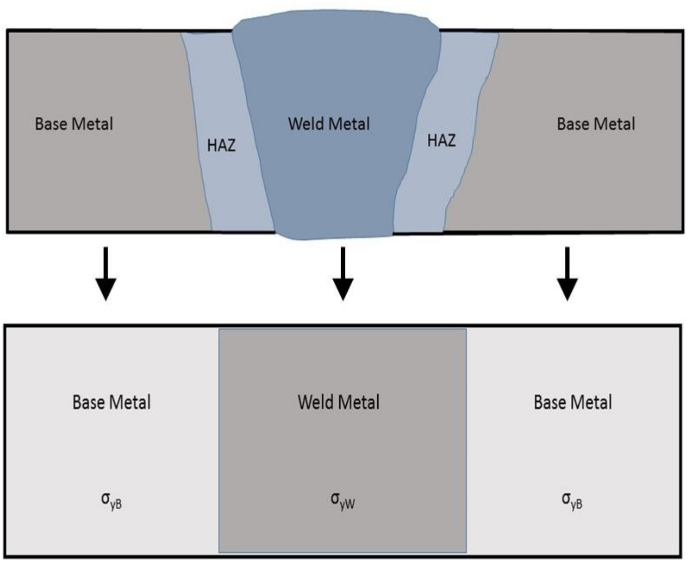

Figure 1: Weld simplification in ECA procedures: homogeneous properties and straight fusion lines

values is being examined. A finite element model of a SENT test was available at Soete Laboratory. In a first step, this models capability of predicting experimental data is being validated using non-welded base material. In a second phase, the potential influence of the hardness to tensile strength transfer function is investigated.

2 FINITE ELEMENT MODEL OF SENT TEST

In a Single Edge Notched Tensile (SENT) specimen, a through-thickness notch is introduced at the side of the specimen. In SENT testing, the specimen is being loaded in tension, see Figure 2. When welded joints are tested the notch is applied in the weld metal or HAZ.

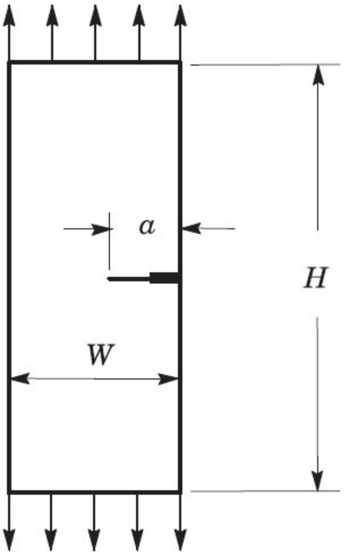

Figure 2: A SENT specimen with W the specimen width,
H the specimen height and a the notch depth [5].

SENT specimens can be provided with so called side grooves to narrow the notch cross section. This is accomplished by machining a groove at both sides of the test specimen in the plane of the notch. This creates a tri-axial stress state at the crack tip, which enhances and straightens the ductile crack front. When side grooves are not applied, the tri-axial stress state in the specimen body transforms into a bi-axial plane stress state at the specimen surface and a typical slightly parallel crack front appears. This phenomenon is called crack tunnelling and makes it difficult to accurately determine the amount of crack propagation.

There exist different methods to determine the Crack Tip Opening Displacement (CTOD). In this work the so called 90° intercept method is applied, unless stated otherwise. The $CTOD_{90}$ is obtained by setting a 90° angle at the initial crack tip and then determine the intersections of this angle with the crack flanks. The $CTOD_{90}$ is calculated as the distance between those two intersections, see Figure 3.

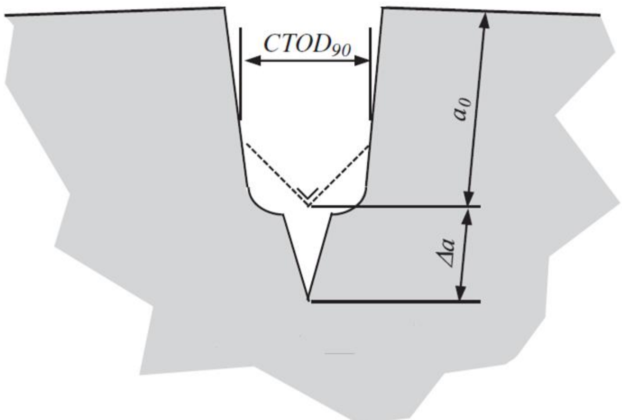

Figure 3: Schematic representation of $CTOD_{90}$ for
growing crack. [10]

At Soete Laboratory a 3D finite element model of a SENT specimen with a stationary (non-growing) crack has been developed for ABAQUS during the PhD of Matthias Verstraete [6], see Figure 4. A small outline of the model and it's working principles will be described next. For a more elaborate description the reader is referred to the work of Hertelé et al. [7]

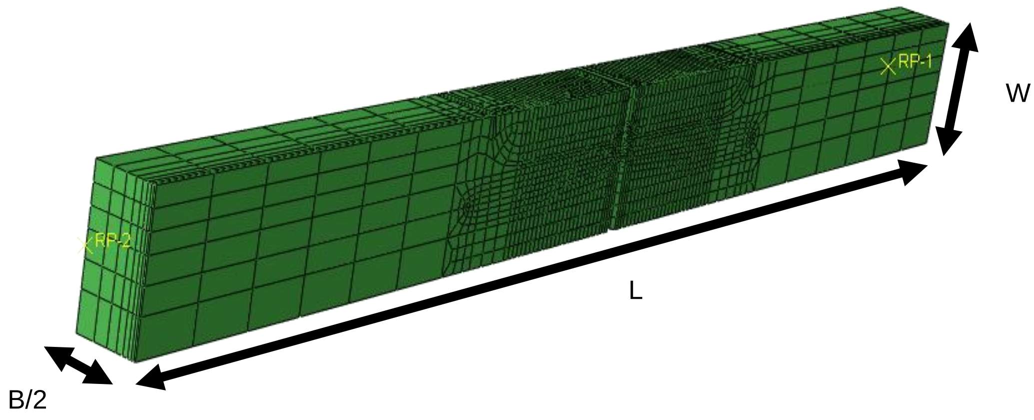

Figure 4: SENT test specimen modelled in ABAQUS with the dimensions used in the parameter description. The width is chosen only half of the real value because of symmetry as this reduces the number of calculations.

The model provides several options to define the material properties of which two will be used in this study. The first option makes use of stress-strain data and is used for homogeneous materials, where all of the elements in the model have the same material properties. This option will be used for the base material simulations.

The second option consulted in this work uses hardness data to define the material properties. Hardness maps of the specific welds are determined and used to assign individual material properties to every element. This option is used to describe heterogeneous weld properties. The model starts by determining the ultimate tensile strength from the hardness. Several correlations exist of which the following two are used in this work:

ISO18265: $$R_m = 3.21 * HV \quad (1)$$

ISO15653: $$R_m = 3.0 * HV + 22.1 \quad (2)$$

The ISO15653 standard also provides a correlation or the yield strength:

ISO15653: $$R_{p0.2} = 2.35 * HV + 62 \quad (3)$$

This leads to a trivial calculation of the yield to tensile ratio (Y/T). For the ISO18265 standard, no yield strength correlation is available, and the Y/T is determined using the FITNET-0.05 procedure:

$$(Y/T)_{avg} = \frac{1}{1.07 + (350/R_m)^{4.8}} \quad (4)$$

For a complete description of the development of the FITNET-0.05 procedure, the reader is referred to the work of Hertelé et al. [7] .

Finally, the strain hardening exponent n is determined using a relation proposed by Hertelé et al.[7]:

$$n = 2.4 + 2.9 \frac{Y/T}{1 - 0.95\, Y/T} \quad (5)$$

It also has to be remarked that the numerical model does not take crack extension into account. Because of that, all of the force versus CTOD curves are only valid until crack extension is initiated.

3 EXPERIMENTAL VALIDATION

The validation study of the model was performed using stress-strain data of homogeneous base material. The geometrical model was configured to correspond to the experimental test specimen, see Table 1.

Table 1: General properties of the base metal SENT specimen

B	W	a_0/W	Initial notch depth	$h_{sidegroove}$
12.50 mm	12.50 mm	0.31	3.875mm	0.625 mm

In order to compare the experimental and numerical results, the corresponding force versus $CTOD_{90}$ curves are plotted, see Figure 5. Both curves tend to match well until crack extension occurs. The finite element model overestimates the crack driving force with a maximum value of 5% at maximum force. In the earlier phase of the experiment, the difference between numerical and experimental curves is limited to 2% to 3%. This proves that the model is sufficiently accurate at predicting the behaviour of a base metal SENT specimen.

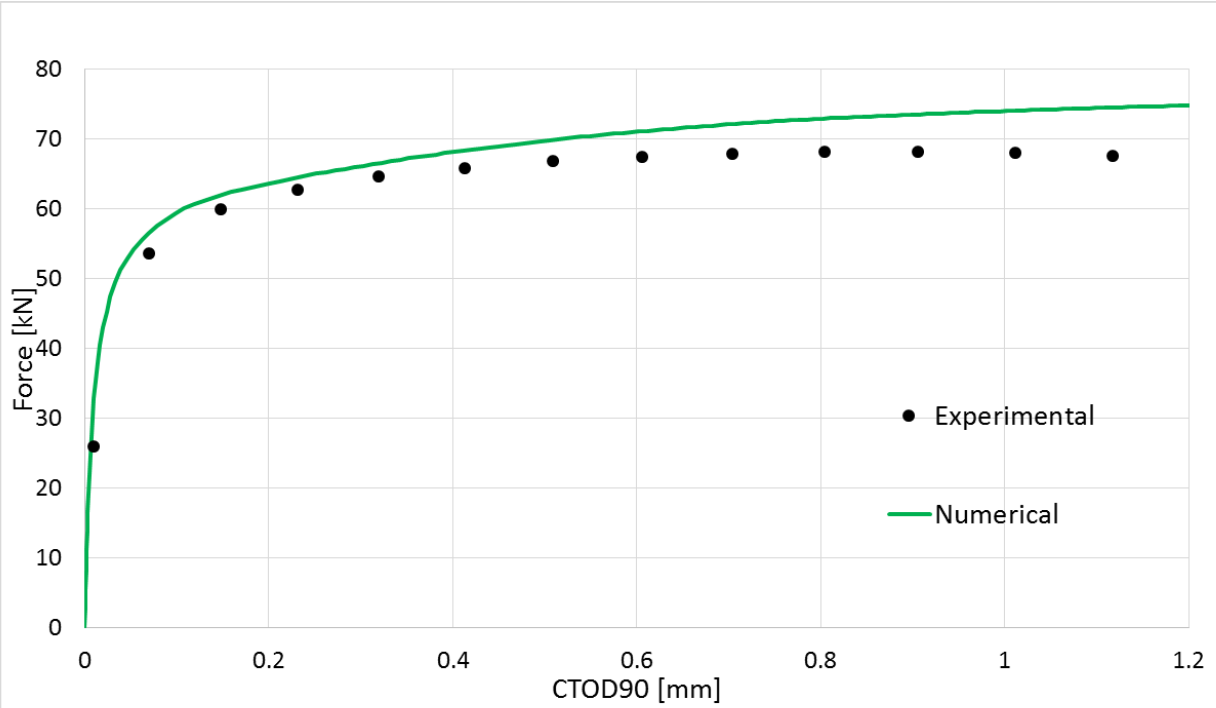

Figure 5: Experimental and numerical force versus CTOD90 curve for the base material specimen

4 EVALUATION OF CRACK DRIVING FORCE FOR DIFFERENT HARDNESS TRANSFER FUNCTIONS

The experimental data used in the transfer-function study come from previous SENT test research performed by Van Gerven [8]. The numerical model is configured to correspond to the experimental test specimen, see Table 2. The hardness map used to calculate the tensile strength parameters was generated by Bally [9], see Figure 6.

Table 2: General properties of the weld metal SENT specimen

B	W	a_0/W	Initial notch depth	$h_{sidegroove}$
9.68 mm	9.70 mm	0.30	2.90 mm	0.48 mm

In **Fout! Verwijzingsbron niet gevonden.** the force versus $CTOD_{90}$ curves of the finite element analysis is depicted for both the ISO18265 and ISO15653 transfer functions. A continuous overmatch with a maximum difference up to 7% in applied force can be determined. This indicates that transfer functions based on the same hardness map create tensile parameters that lead to a significant difference in model outcome.

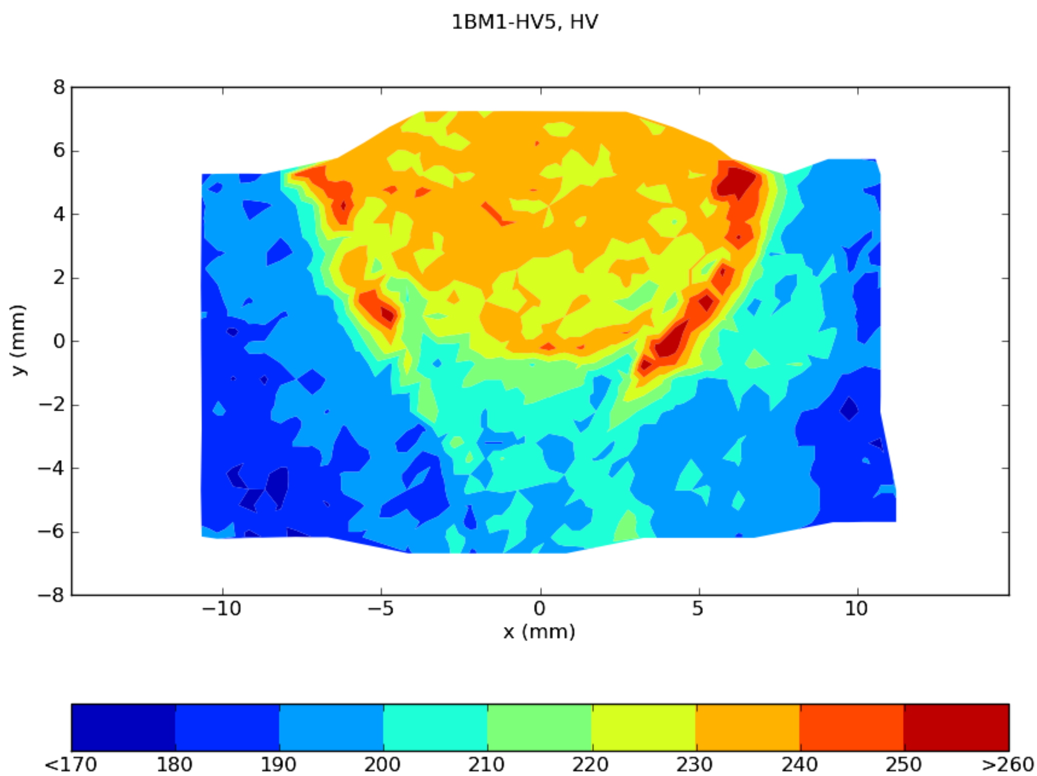

Figure 7: Hardness map of the weld from which the SENT specimen was extracted [9]

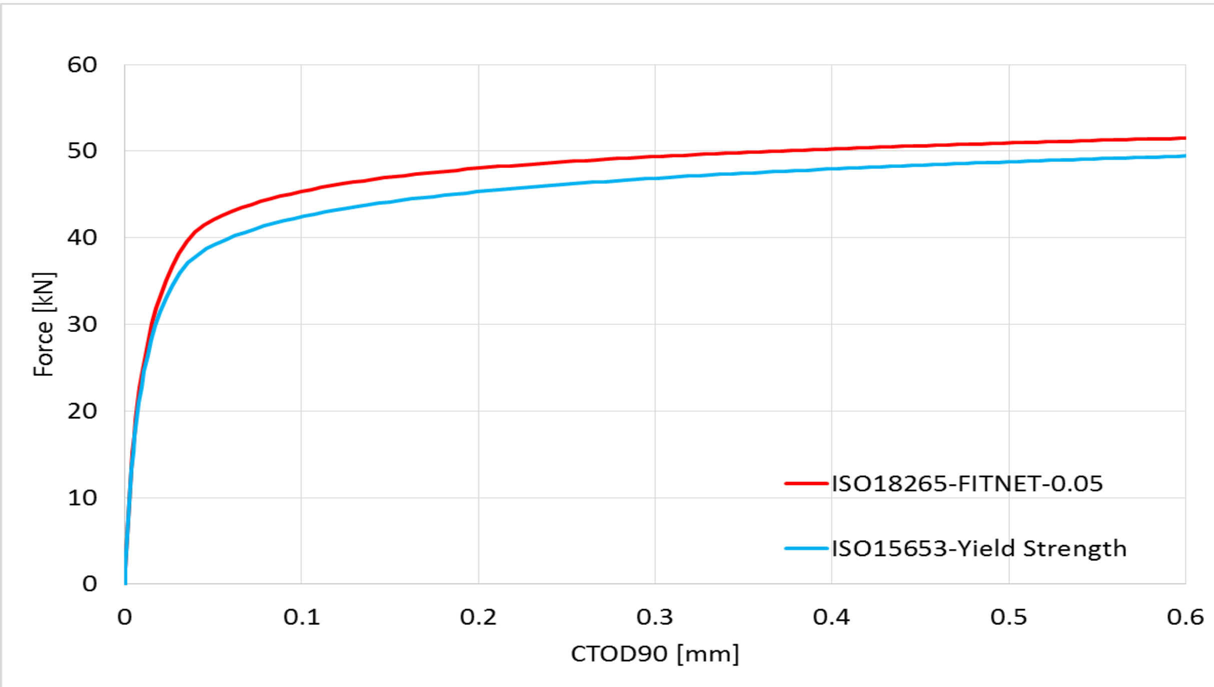

Figure 6: Force versus $CTOD_{90}$ simulation with two different transfer functions

The mismatch between the two crack driving forces appears to be caused by the difference in tensile strength parameters that are calculated from the hardness values that occur in the weld examined (170 HV – 290 HV). From Figure 8 it can be seen that the ISO18265 procedure systematically generates higher tensile strength parameters than the ISO15653 procedure. Especially at the round bar and slip line average hardness, which are representative values for the strength when crack driving force respond is regarded. The round bar average hardness is the average hardness calculated from a circle with diameter 6mm at the centre of the weld and the slip line average hardness is the average hardness that occurs along the slip lines drawn at the tip of the notch. The difference in strength parameters is significant and declares the difference in model outcome.

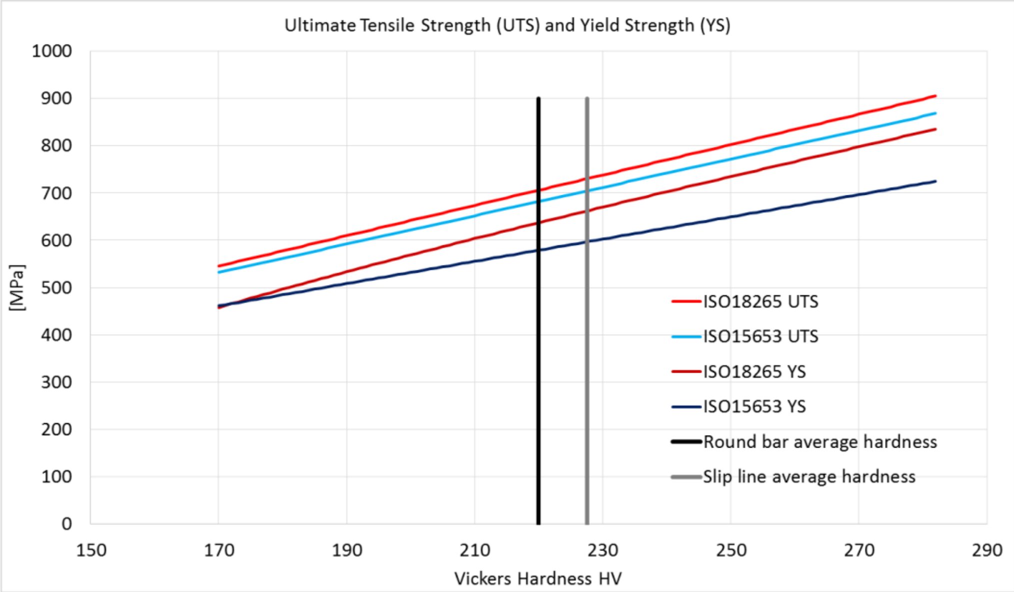

Figure 8: Ultimate tensile strength (UTS) and yield strength (YS) calculated from the ISO18265 (and FITNET-0.05) and ISO15653 standards based on the hardness range that occurs in the weld metal specimen.

5 CONCLUSIONS

At Soete Laboratory, SENT tests can be performed experimentally and numerically. From the base material simulation it is clear that the developed model is capable of predicting the SENT specimen's behaviour. Hardness maps provide a straightforward method to implement weld strength heterogeneity into the finite element model. Hardness to tensile strength transfer functions are available and easily implemented in the model. It should however be noted that different types of transfer functions lead to a different outcome of the model and the exact definition of hardness transfer function strongly influences the crack driving force response of the finite element specimen.

6 ACKNOWLEDGEMENTS

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