NAFEMS India

International NAFEMS Conference on Engineering Analysis, Modeling, Simulation and 3D-Printing (NAFEMS-3D) – 2016

Full paper

Sensitivity study of crack driving force predictions in heterogeneous welds using Vickers hardness maps

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Abstract

Weld flaws often require an engineering critical assessment (ECA) to judge on the necessity for weld repair. ECA is a fracture mechanics based prediction of the integrity of welds under operating conditions. Adding to the complexity of an ECA is the occurrence of local constitutive property variations in the weldment (‘weld heterogeneity’). Their quantification is important to allow for an accurate assessment. Hereto, hardness measurements are widely adopted given their theoretical relation with ultimate tensile strength. However, various standards and procedures report a wide variety of different hardness transfer functions and additionally recognize substantial scatter in predictions of strength. Within this context, this paper investigates the suitability of hardness mapping to perform an accurate weld ECA. A finite element analysis has been conducted on welds originating from steel pipelines to simulate their crack driving force response using single-edge notched tension (SE(T)) specimens. Vickers hardness maps and hardness transfer functions are combined to assign element-specific constitutive properties to the model. The resulting crack driving force curves are probed against experimental results. The variable agreement between simulations and experiments highlights the need for further research into the characterization of local constitutive properties of heterogeneous welds. A hardness transfer procedure based on all weld metal tensile testing appears to be particularly promising.

Keywords: Weld, Heterogeneity, Crack driving force, Vickers hardness, SE(T) specimen.

1. Introduction

Engineering Critical Assessment (ECA) is a process of characterizing the serviceability of a structure. ECA is a fracture mechanics based approach which is utilized to predict the integrity of defected connections subjected to loading. This technique involves the quantification of crack driving force (for instance expressed in terms of Crack Tip Opening Displacement – CTOD) under operating conditions. Very often, ECA is applied to welds given the likely presence of natural flaws.

A wide range of standards and procedures are available in order to gauge flaws present in welds based on size, location, orientation and stress development around them due

Nomenclature

σ	True stress (MPa)
ε	True strain (-)
σ_y	Yield stress (MPa)
ε_y	Yield strain (-)
α	Yield offset (-)
n	Strain hardening exponent
R_{p02}	Yield strength (MPa)
R_m	Ultimate tensile strength (MPa)
Y/T	Yield to tensile ratio
E	Young's modulus (MPa)
P	Tensile force (N)
HV	Vickers hardness
$CTOD$	Crack tip opening displacement (mm)
$SE(T)$	(clamped) Single-edge notched tension specimen

to loading. The main drawback of these methods is that they consider the defect to be surrounded by a homogeneous material. Although this assumption is valid for a base metal, it involves an approximation for defects located in a weld region. This is because of the presence of local strength variations in weldments which is due to the occurrence of numerous heat cycles (heating and cooling) during welding process. Hence, the quantification of this heterogeneity is a challenge as they are unique and distinct for each weld metal.

The measurement of Vickers hardness of a weld sample is one of the most common techniques to quantify local strength properties. Hardness is known to relate to ultimate tensile strength R_m (MPa) , the equation expressing such relation being referred to as a 'hardness transfer function'. Similar transfer functions may be constructed between hardness and yield strength R_{p02} (MPa), and strain hardening, thus covering the entire stress-strain behavior. Hereby, strain hardening can be expressed in terms of the exponent n, assuming power-law hardening by means of the Ramberg-Osgood equation [1]:

$$\frac{\varepsilon}{\varepsilon_y} = \frac{\sigma}{\sigma_y} + \alpha\left(\frac{\sigma}{\sigma_y}\right)^n \tag{1}$$

Here, σ and ε represents true stress and strain while σ_y= R_{p02} and ε_y represents yield strength and strain respectively. α is a yield offset parameter, where $\alpha\varepsilon_y = 0.002$ is the plastic strain corresponding to 0.2% proof stress and n is the strain hardening exponent.

Soete Laboratory has developed numerical tools to exploit the hardness values obtained by creating several hundreds of indentations on a weld sample ('hardness mapping'). The hardness values from such maps are assigned to each element of a finite element model which in turn converts them to stress-strain properties using assumed transfer functions. This technique will be employed in this work to study the crack driving force behavior of a heterogeneous weld and its level of agreement with experimental results. The feasibility of several transfer procedures to convert hardness to constitutive model parameters has also been analyzed on the basis of experimental results.

2. Background

The early work of Tabor [2] reported on relations between hardness and constitutive behavior. Hardness was found to be related to the stress at a representative strain level, which for Vickers hardness was around 0.08. Given the typical ductility levels and strain hardening characteristics of steel, this stress is close to the R_m. Therefore, hardness has very often been used to estimate ultimate tensile strength R_m. As hardness fails to provide the full range of strain hardening behavior, the approximate nature of these estimates is acknowledged and quantified in the standard ISO 18265 [3]. This standard contains tabulated conversion data between hardness and R_m and corresponding scatter bands.

Another relevant international standard is ISO 15653 [4], which mentions HV transfer functions for weld and base material separately. Unlike ISO18265, it also mentions relations between hardness and yield strength. For instance, given transfer functions for weld metal are:

$$R_{p02} = 2.35\, HV + 62 \tag{2}$$

$$R_m = 3.0\, HV + 22.1 \tag{3}$$

Researchers have independently constructed hardness transfer functions for their specific purposes. For instance, Hertelé et al. [5] termed hardness as a tool to produce realistic (but not necessarily the actual) local stress-strain properties of fusion welds with variable yield strength and strain hardening behavior. They considered power law hardening according to the Ramberg-Osgood equation (Eq. 1) and determined its parameters (yield strength σ_y, yield strain ε_y, strain hardening exponent n and yield offset α) as follows:

Ultimate tensile strength (R_m) is calculated using hardness values according to a linear regression fit of conversion data for steel tabulated in [3],

$$R_m = 3.21\, HV \tag{4}$$

Yield to tensile ratio Y/T is derived from R_m, using a large dataset of stress-strain characteristics of steels [5,6] i.e.

$$\frac{Y}{T} = \frac{1}{1.07 + (350/R_m)^{2.5}} \tag{5}$$

The data set is further referred to as FITNET dataset (and Eq. 5 as FITNET equation) as it was used to calculate an upper bound equation for Y/T. in FITNET. Note that Eq. 5 does not represent this upper bound, but an average value of Y/T. Yield strength σ_y and strain ε_y are obtained by,

$$\sigma_y = R_{p02} = R_m . \frac{Y}{T} \text{ and } \varepsilon_y = \frac{\sigma_y}{E} \tag{6}$$

where E is Young's Modulus considered as 206.9 GPa in this entire study.

The yield offset α is taken equal to $0.002/\varepsilon_y$, in which case the yield strength represents the 0.2% proof stress. Finally, strain hardening is closely related to Y/T according to Considère's necking criterion. Their relation has been curve-fitted into:

$$n = 2.4 + 2.9 \frac{Y/T}{1 - 0.95\, Y/T} \tag{7}$$

Assuming the procedure outlined above, they determined the crack driving force response of welds by transferring local weld hardness data into stress-strain input using the above equations for a finite element model. The approximate nature of the above mentioned hardness transfer functions may influence the fracture mechanics based prediction of weld integrity in presence of defects. In this research paper, an attempt is made to quantify expectable variations and a calibration procedure is developed to avoid these variations.

3. Material and Methods

3.1 Experimental program

The experimental data reported in this paper have been obtained from a girth weld connecting 36" (914.4 mm) diameter and 17.1 mm thick steel pipes of API 5L grade X70 steel [7] (specified minimum yield strength 485 MPa). The pipe was shielded metal arc welded (SMAW) and the weld procedure intended to produce strength properties that even-match the base metal. The following material characterizations were performed on each sample (three samples considered) and are discussed below:

- Weld macrographs and 5 kgf Vickers hardness (HV5) mapping
- Single-edge notched tension or SE(T) testing
- All weld metal tensile testing or AWMTT

Soete Laboratory has a Vickers hardness measurement device which is capable of automatically producing several hundreds of indentations within the boundaries of the sample and provide hardness values at each indent. Hereby, the distance between adjacent hardness indentations is sufficient to avoid interactions. The hardness maps are shown in Figure 1. Closely observing the weld, Heat Affected Zone (HAZ) softening can be evidently seen. The root of the beveled weld has the softest region while the cap being the hardest confirming the dependence of heat cycles on hardness variations throughout the weld. In between cap and root, the presence of different weld passes

Note that the reason for choosing three samples from same pipe is to account for variations in weld properties in the direction of welding. As these appear limited, the hardness maps can serve as an input for the analysis of the SE(T) and AWMTT test specimens, which were extracted at slightly different (but adjacent) positions in the weld.

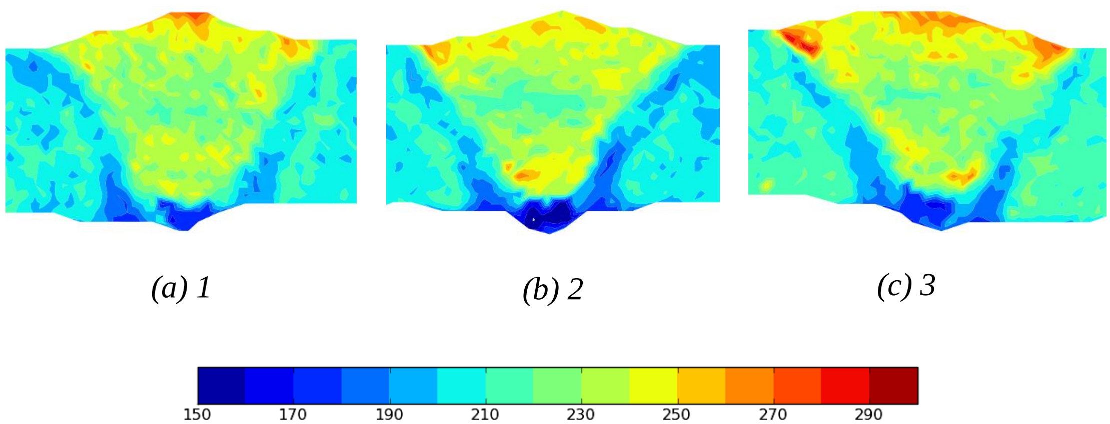


Figure 1: Vickers hardness maps of three weld samples 1 (a), 2 (b) and 3 (c) showing the range of hardness variations.

The extracted specimens for SE(T) testing had a square cross section $B = W = 14$ mm. The notch, placed at the center of the specimen, has depth $a = 4.5$ mm and the side groove depth was 1.13mm. The daylight length of the specimen was 200 mm. Testing was performed on a 150 kN universal tensile machine with the assistance of hydraulic clamps which offered clamped support (no rotational degrees of freedom). The crack tip opening displacement was measured using the double clip gauge method as explained in [8]. The test was continued beyond necking until the load dropped to 85% of the maximum load. The point of crack initiation was identified using direct current potential drop. The focus of this work is to remain in plastic region before crack initiation of Force *(P)* versus CTOD curve to analyze the feasibility of transfer functions in simulations.

All weld metal tensile testing is a general tensile test to determine stress-strain properties of a test sample which is entirely extracted from a weld region as the name suggests. This test is performed to experimentally calibrate hardness transfer function which is detailed further in this paper. It is important to note that SE(T) and all weld metal tensile test specimens were extracted next to the HV5 specimens in the girth weld and can be individually associated to each other forming 3 sets of specimens.

3.2 Numerical model

In order to study the sensitivity on crack driving force response of different transfer functions, a three dimensional side grooved SE(T) specimen was finite element modeled using the commercial software ABAQUS (version 6.11). The meshing strategy to this model has been developed in reference [8]. The assignment of element specific stress-strain properties in accordance with the hardness contour to the finite element model was based on the work by Hertelé et al. [5].

The model is shown in Figure 2 and 3. Model geometry and dimensions were chosen in agreement with the experiments. Note that the total length of the specimen model was taken 200 mm, which is the daylight length of the specimens used in experiments. The rotational degrees of freedom of the end planes were inhibited, thus reflecting a clamped specimen. The model consisted of around 20000 brick elements having eight nodes with a reduced integration scheme. Incremental plasticity was defined by isotropic hardening with the von Mises yield criterion, obeying the Ramberg-Osgood model (Eq. 1). Crack initiation and ductile tearing were not taken into account. Crack tip opening displacement (CTOD) was considered as crack driving force characteristics and was calculated using Rice's 90^0 intercept method [9].

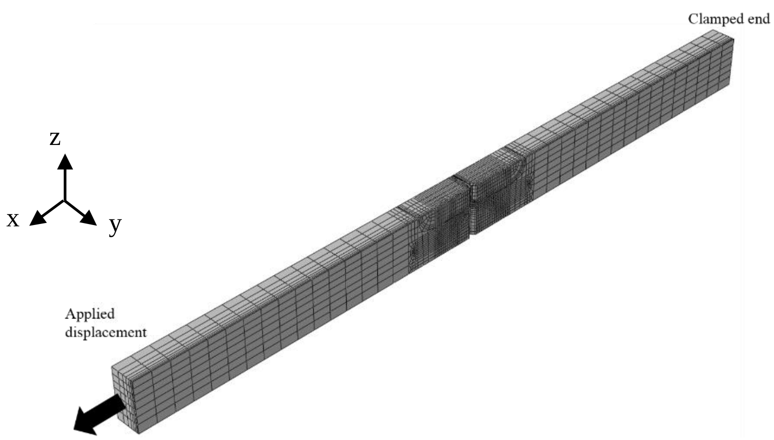


Figure 2: The complete Finite Element (FE) model of SE(T) specimen

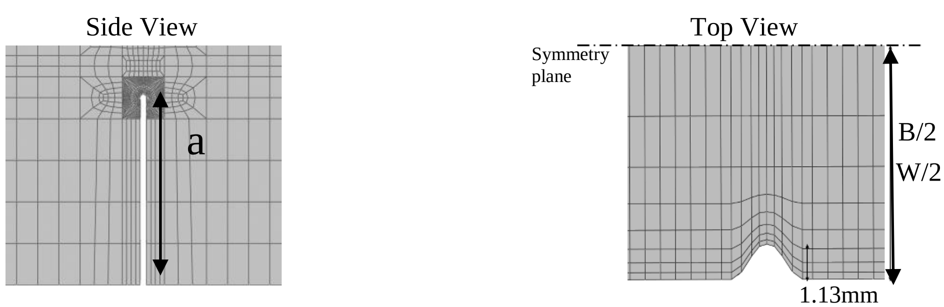


Figure 3: Crack depth and side grooves in SE(T) model.

3.3 Transfer functions

The important focus of this work is to understand the sensitivity of equations used for conversion of hardness values to Ramberg-Osgood parameters (Eq. 1). The three combinations of transfer functions were formulated based on available literature in order to analyze the sensitivity. They are 'ISO18265+FITNET', 'ISO15653+FITNET' and 'ISO15653' as shown in Table 1.

Table 1: Transfer function combinations from literature

	ISO18265+FITNET	***ISO15653+FITNET***	***ISO15653***
$\boldsymbol{R_m}$	$3.21\,HV$	$3.0\,HV + 22.1$	$3.0\,HV + 22.1$
$\boldsymbol{Y/T}$	$\frac{1}{1.07 + (350/R_m)^{2.5}}$	$\frac{1}{1.07 + (350/R_m)^{2.5}}$	$\frac{R_{p02}}{R_m}$
$\boldsymbol{R_{p02}}$	$R_m * Y/T$	$R_m * Y/T$	$2.35\,HV + 62$

The strain hardening exponent for three different combinations of transfer functions were obtained from Y/T using Eq. 7.

Another two transfer function were developed based on experiments. They are AWMTT+FITNET and Optimized AWMTT. The HV_{AWMTT} is the average hardness value obtained from HV5 mapped weld at the location where the AWMTT specimen is extracted. This location is shown for one of the samples in Figure 4, in terms of its circular boundary.

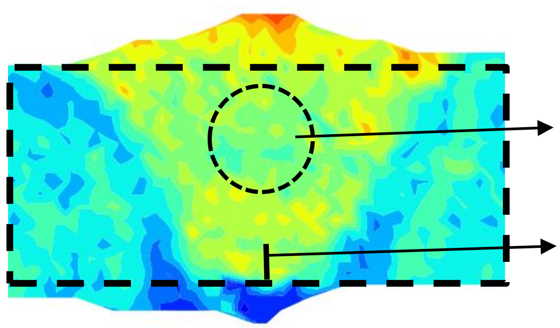


Figure 4: Location of extraction of All weld metal tensile test(AWMTT) sample.

In an attempt to improve the error of correspondence between numerically and experimentally obtained in P-CTOD plots using transfer functions, the ultimate tensile strength values ($R_{m(AWMTT)}$) from three AWMT tests were collected. These values were used to calculate ultimate tensile strength (R_m) and hence the other parameters. The following relations are put forward for AWMTT+FITNET procedure:

$$\boldsymbol{R_m} = R_{m(AWMTT)} * \frac{HV}{HV_{AWMTT}} \tag{8}$$

Eq. 5, 6 and 7 i.e. FITNET equations were used for calculation of other parameters.

The reason for choosing FITNET equation even though we have the stress-strain properties from AWMTT is that the former procedure provides variable strain hardening behavior which is realistic. However, as a consequence, the AWMTT-FITNET procedure is semi experimental.

Least square curve fitting technique [10] was adopted for stress-strain curve obtained from AWMTT in order to find best fitting Ramberg-Osgood curve. The curves can be seen in Figure 5. The following relations for optimized AWMTT are postulated:

$$\boldsymbol{R_m} = R_{p02(AWMTT)} * \frac{HV}{HV_{AWMTT}} \text{ and } \frac{\boldsymbol{Y}}{\boldsymbol{T}} = \frac{R_{p02(AWMTT)}}{R_{m(AWMTT)}} \tag{9}$$

with $R_{p02(AWMTT)}$ taken from the best fitting Ramberg Osgood curve. Theoretically, this examination is expected to provide better correspondence to experiments as this calibration entirely based on experimental input.

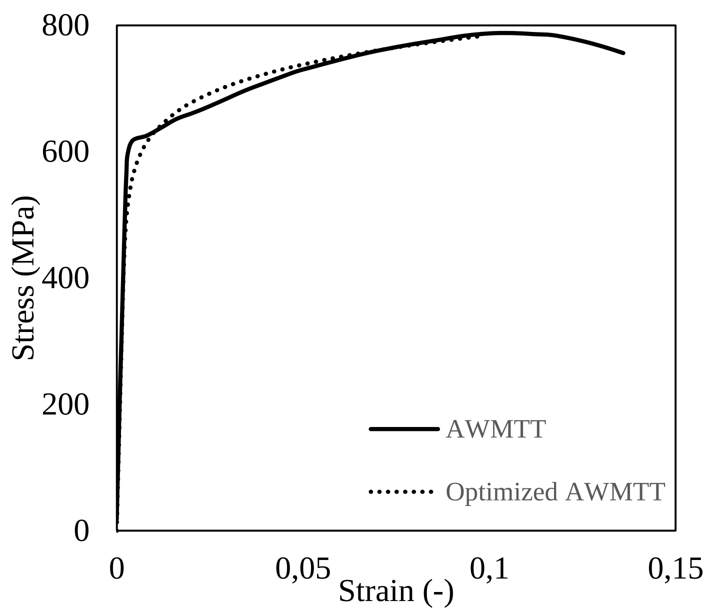


Figure 5: Stress-Strain curve of AWMTT and optimized AWMTT

4. Results and Discussions

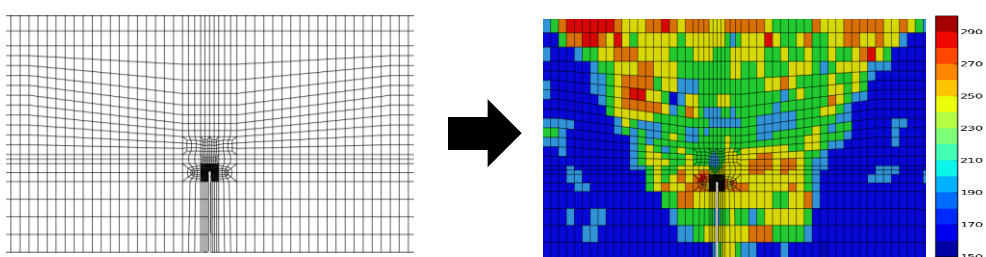
This research was initiated with the aim to understand the variable crack driving force predictions using different transfer functions to obtain Ramberg-Osgood parameters from Vickers hardness values (HV5). The *(P)* versus CTOD curves of SE(T) experiments and simulations served as the output to investigate these variations.

The behavior of three transfer functions from published results are studied in section 4.1. Section 4.2 shows the results of SE(T) simulations whose properties are defined using AWMTT.

4.1 Sensitivity analysis using standard transfer functions

The relations mentioned in Table 1 were adopted to obtain Ramberg-Osgood parameters of the material from HV5 values. These relations are employed to define element properties of the finite element model for the weld region. The element specific properties are based on Ramberg-Osgood parameters. The outcome of this process is shown in Figure 6.

Force (P) vs CTOD plots are obtained by using finite element simulation. As the crack initiation and ductile tearing is neglected, the focus is in the region of plasticity up to crack initiation. The elastic part remains constant for all the tests as is ignored. Hence the output CTOD is plotted in terms of plastic rather than total CTOD.



(a) (b)

Figure 6: (a) 2D View of the SE(T) FE model before and (b) after assigning element specific strength properties.

Figure 7 displays the *(P)* versus CTOD plots of SE(T) specimen, sample 1, subjected to tensile loading. It reveals variations in force that are the results of different transfer functions used to obtain strength characteristics. Simulated curves are compared with the experimental P-CTOD curve, which was smoothened using a moving average technique to limit the deviations observed during clip gauge measurements. From the tests conducted, it was evident that 'ISO18265+FITNET' has acceptability issues throughout while 'ISO15653+FITNET' and 'ISO15653' displayed better agreement with the experimental values.

By comparing SE(T) simulations to experiments, it was found that 'ISO15653' showed the best agreement for *P* versus CTOD curves. The same exercise was performed for the samples 2 and 3. The plots can be viewed in Figure 8.

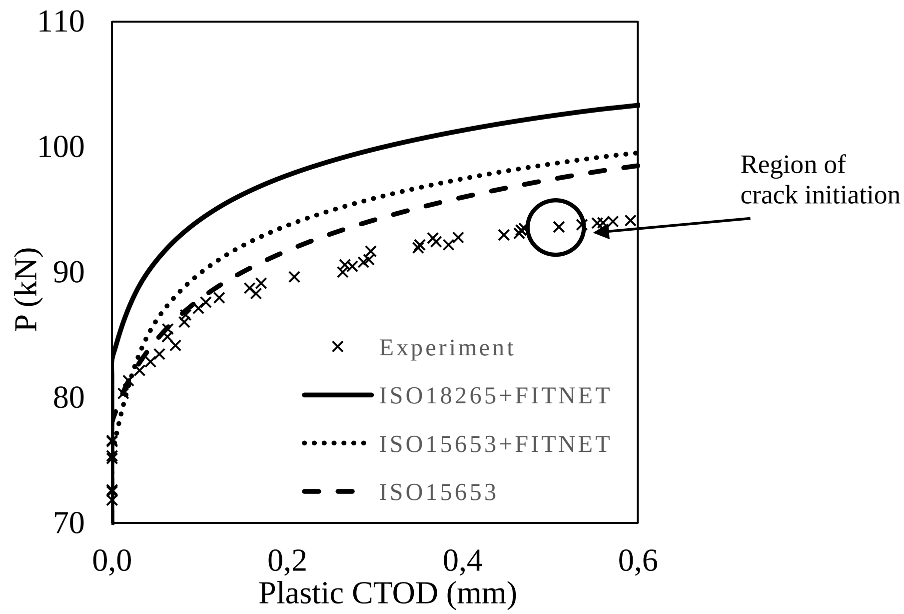


Figure 7: P vs CTOD plot showing experimental and numerical results using different combinations of transfer functions for weld sample 1.

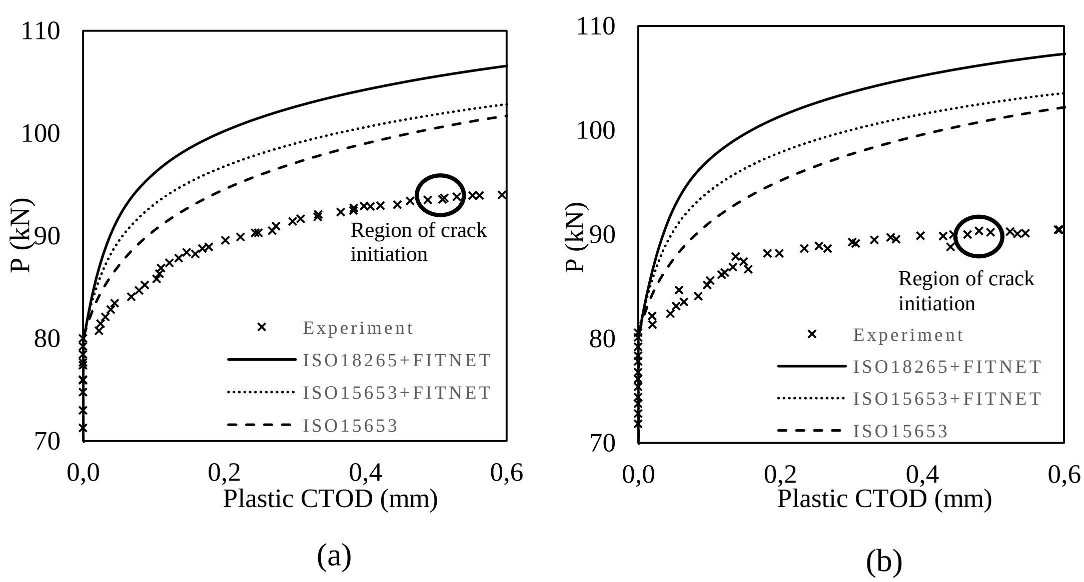


Figure 8: P vs CTOD plots for the samples 2 (a) and 3 (b) using different transfer functions

By observing the plots from Figure 7 and 8, it can be again confirmed that ISO15653 results in better agreement with the experimental curve for the investigated welds. Recall that, yield and ultimate tensile strengths are entirely based on the hardness values from which Y/T and n are calculated in ISO15653. The important parameters for analyzing plasticity are ultimate tensile strength and yield strength and hence this combination defines the plastic region of the test. A thorough analysis is required to confirm this observation by choosing weld samples having different geometry, mismatch ratio etc.

4.2 Sensitivity analysis using All Weld Metal Tensile Tests

Simulations were performed on SE(T) specimens using Eq. 5,6,7 and 8 as transfer functions to find different parameters and input being AWMTT values. The correspondence of semi-experimental 'AWMTT+FITNET' procedure based *P*-CTOD curve to the experiments is not acceptable as it deviates from ISO15653 by a big margin which is visible in Figure 9.

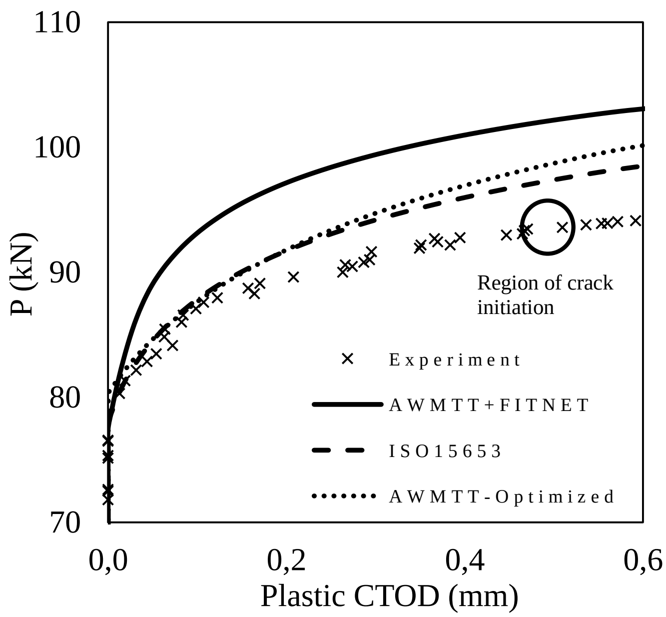


Figure 9: P vs CTOD plot involving AWMTT and optimized AWMTT results for Sample 1

In contrast, the fully experimental AWMTT transfer function provides a better agreement to experiment, especially during the initial phase of plasticity. It is in par with ISO15653 but deviates from experiment as CTOD increases. Similar graphs are plotted for optimized AWMTT and ISO15653 using samples 2 and 3 to analyze the deviations in detail and are shown in Figure 10.

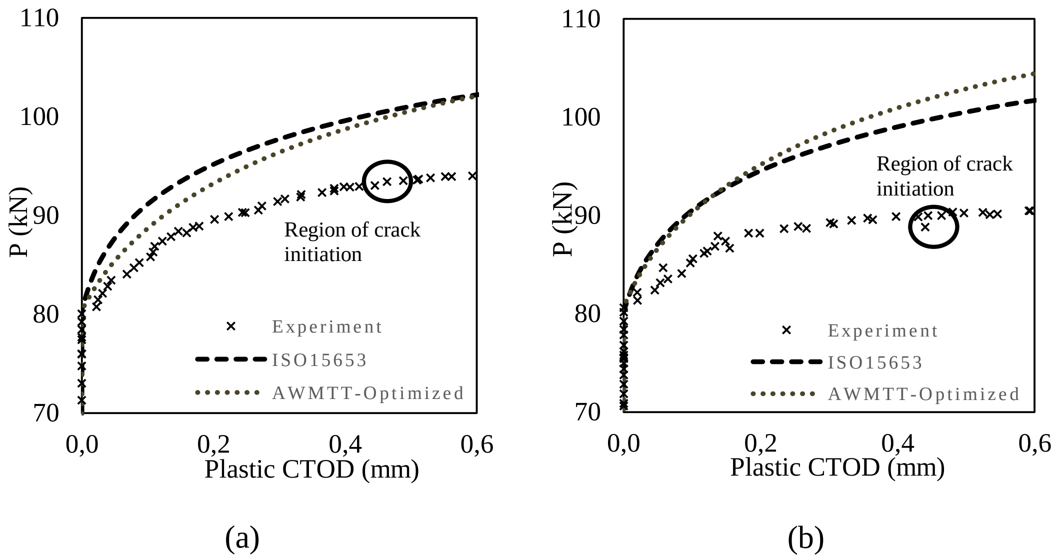


Figure 10: P vs CTOD comparing optimized AWMTT results to ISO15653 for weld samples (a) 2 and (b) 3

From the plots obtained, the optimized AWMTT results show marginally better agreement than ISO15653 during the initiation of plasticity. As the deformation increases, the numerical value deviates. Here, the point of interest for the study is up to crack initiation, which by definition corresponds with a measured crack extension of 0.2 mm or roughly 5% of initial notch depth. Choosing the point of crack initiation is difficult during the experiment and is an approximate value [8]. This may result in similar decrease in load capacity thus explaining the divergence of simulations and experiments. Here, the crack initiation point is taken as the average of 3 experiments.

The crucial outcome from optimized AWMTT results is that the agreement to experiments is satisfactory even though the round bar tensile test specimens were extracted away from the location of the notch. An approximate notch location is shown in Figure 4. This is pivotal for the analysis of heterogeneity aspects present in the weld which is beyond the scope of this paper.

5. Conclusions

A detailed sensitivity analysis has been performed considering the prospect of crack driving forces on weld samples extracted from a pipeline. The sensitiveness of the force and Crack Tip Opening Displacement (CTOD) curve to the local constitutive parameters calculated from Hardness (HV5) values using different techniques has been analyzed. Single Edge Notched Tension (SE(T)) specimens were utilized for this study and numerical techniques were used to assign element specific properties obtained from hardness maps for modelling welded connections. Experimental SE(T) results were considered for comparison.

The results gathered from this research showed satisfying trends corresponding to the numerical technique used to study crack driving force response of a flawed weld. While the hardness transfer function given by ISO15653 showed the best agreement to experiments among the other analytical procedures available, All Weld Metal Tensile Testing (AWMTT) opens new doors for an experimental calibration of hardness transfer functions. This idea shows promising trends, notwithstanding that the AWMTT samples weld metal different from the notch tip location.

At this point, it is hypothesized that the satisfactory agreement of ISO15653 transfer functions may be of variable nature for other welds, whereas the experimentally calibrated (AWMTT based) test procedure is more constant in terms of accuracy. Further work is required to confirm this hypothesis.

6. Acknowledgements

The authors would like to acknowledge FWO Vlaanderen (Research Foundation — Flanders, research grant nr. G.0609.15N) and researchers Mr. Diego Belato Rosado and Mr. Kaveh Samadian for the support provided during this research. The research leading to these results has received funding from the European Union's Research Fund for Coal and Steel (RFCS) research programme under grant agreement no. RFSR-CT-2013-00025.

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