REDUCED-THICKNESS CVN TESTING TO REPRESENT SLANT FAILURE OF PIPELINES

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Abstract: To avoid longitudinal ductile crack propagation along a gas pipeline, the Batelle Two Curve method is used during pipeline design. This method states that a running crack will be arrested if the gas decompression velocity exceeds the crack propagation speed at the internal gas pressure. The crack propagation curve is scaled by impact energy values obtained through Charpy V-Notch (CVN) testing. However, for high-strength steel grades this scaling leads to unconservative predictions, because the experiment does not sufficiently represent the pipeline failure mode. The CVN specimen exhibits mainly mode I failure, without significant shear lips, while real failure is a combined mode often described as slant failure. In the present study, instrumented CVN tests are carried out on samples with different thickness reduction levels. To get a better insight in the crack initiation and propagation behaviour, the CVN test is simulated by finite element analysis. The dissipated energy and resulting fracture surfaces can be successfully represented. It is observed that slant failure is promoted by reducing the specimen thickness. In addition, the specific absorbed energy is decreased. However, most of the difference of absorbed energy is in crack initiation. This means that the fraction of the total energy dissipated in crack propagation is increased for reduced thickness specimens, making it a possible tool to assess the resistance of a material to crack propagation, provided that brittle fracture is avoided.

Keywords: fracture mechanics; Charpy; pipeline; slant failure; finite element analysis

1 INTRODUCTION

High pressure pipelines are commonly designed using the Battelle Two Curve Method (BTCM) [1] to avoid longitudinal running cracks. This method is illustrated in Figure 1. If there is a crack in a gas pipeline, the internal gas pressure delivers a crack driving force, while due to the occurrence of a crack, the gas will decompress and the pressure will drop with a certain speed. Next to this, the pipeline material toughness delivers the crack resistance force which influences the crack propagation speed. The BTCM stipulates that crack propagation will occur at a given internal gas pressure if the crack propagation speed exceeds the gas decompression velocity.

According to the BTCM, the crack propagation curve should be scaled by Charpy V-notch (CVN) impact test results. However, the original BTCM was calibrated using test results of full-scale burst tests of pipeline steels with CVN upper shelf energies below 100 J while modern high-strength steel grades exhibit CVN impact values well above this value. Recent results have shown that the original BTCM correlations are no longer valid for these high-strength steel grades [3-4].

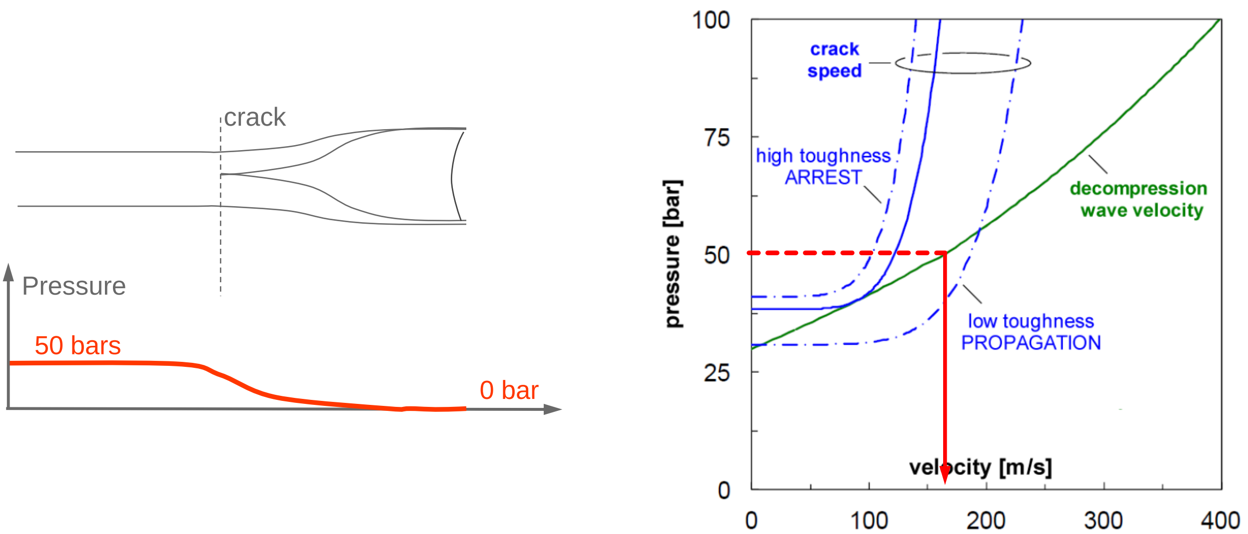

Figure 1: left: pressure evolution during longitudinal crack propagation; right: Batelle Two Curve Method [2].

For high-strength steels the high CVN values are mainly achieved through an increase of the crack initiation energy [5-6], while the crack propagation energy is defining the crack propagation resistance. In addition, the Charpy specimen exhibits mainly a mode I failure without shear lips, while full-scale burst tests show a combined failure mode described as *slant failure* [7]. In this study it is shown that slant failure can be obtained during Charpy impact testing by reducing the specimen thickness. In addition, the crack propagation energy becomes a more important part of the total absorbed energy.

2 REDUCED THICKNESS CVN TESTING

In the present study CVN tests are carried out on samples machined from an API 5L X70 pipeline steel of 19.5 mm thickness. Next to standard CVN specimens of 10 mm thickness, reduced-thickness samples are tested with a thickness of 5.0 mm and 2.5 mm. Impact tests are carried out on an instrumented Zwick 750 J hammer according to ISO148-1 [8]. The upper shelf energy of the X70 steel is close to 270 J, which is well above the limit of 100 J for which the original BTCM has been developed.

By reducing the sample thickness, the stress triaxiality at the Charpy V-notch of specimen is affected. As a result, the fracture behaviour of the samples is changed. The reduced thickness CVN specimens clearly show a different failure mode than the standard 10 mm thick specimens. Figure 2 shows two specimens after testing. Note that the section views of the fracture surfaces exhibit two shear lips (these views are obtained by cutting the samples in the plane normal to the crack propagation direction at mid ligament length). A significant thickness reduction was observed in both test specimens. The shear lips are most pronounced for the 2.5 mm specimen. Hence slant failure is promoted by reducing the CVN specimen width.

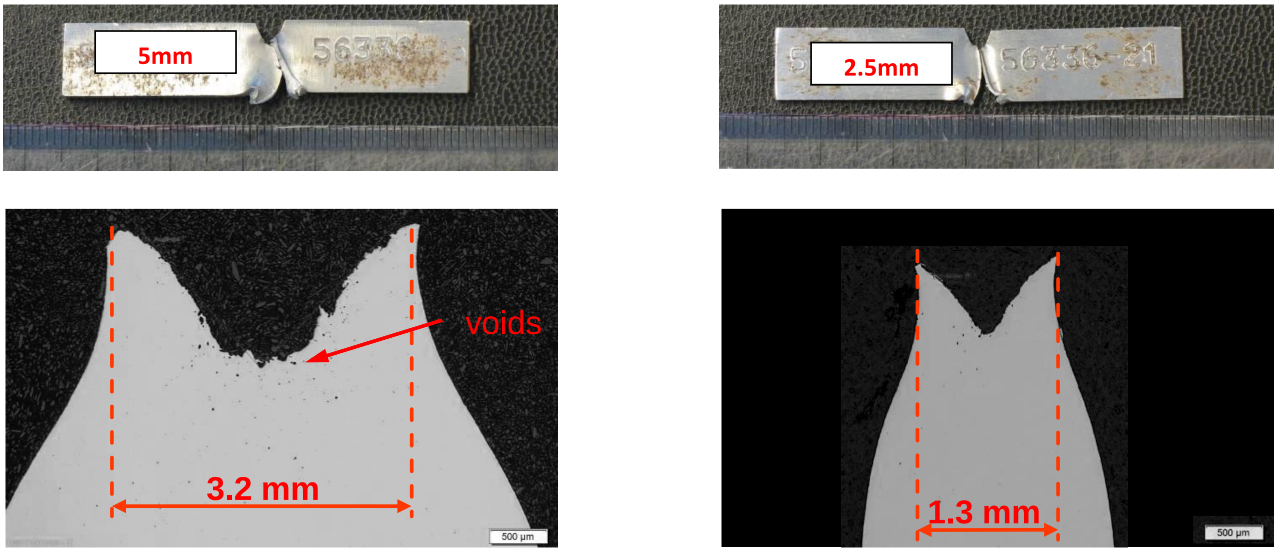

Figure 2: Reduced thickness CVN specimens after impact testing. The bottom pictures show a section view of the slanted fracture surface with two shear lips.

In the left graph of Figure 3 the normalized force-displacement measurements are shown for the 10 mm, 5.0 mm and 2.5 mm thick samples tested at room temperature. The curves are normalized by dividing the measured force by the sample thickness in order to facilitate comparing the results. The curves do not exhibit sudden drops of the force, hence the crack propagation is fully ductile. In the graph on the right, the force-displacement curve is shown of one of the 5.0 mm samples. The crack initiation energy corresponds to the area (1) under the curve, while the total crack propagation energy corresponds to area (2). In the area (2b), there is a linear decrease of the measured force. In this region, the crack is propagating at a constant speed. This area of linear crack propagation is most representative to running ductile fracture.

The main difference between the tests of the samples with different thicknesses is at the beginning of the test. The displacement at maximum load (point of crack initiation) is smaller when the sample thickness is reduced. The 10 mm thick samples had a slightly different behaviour with a short section with a different slope just after the maximum load. In Table 1 the total absorbed specific energy and the percentage of the linear propagation energy compared to the total energy are listed. It is clear that the specific energy decreases with decreasing specimen thickness, while the fraction of the linear propagation energy increases. Hence, the test results become more representative for ductile crack propagation.

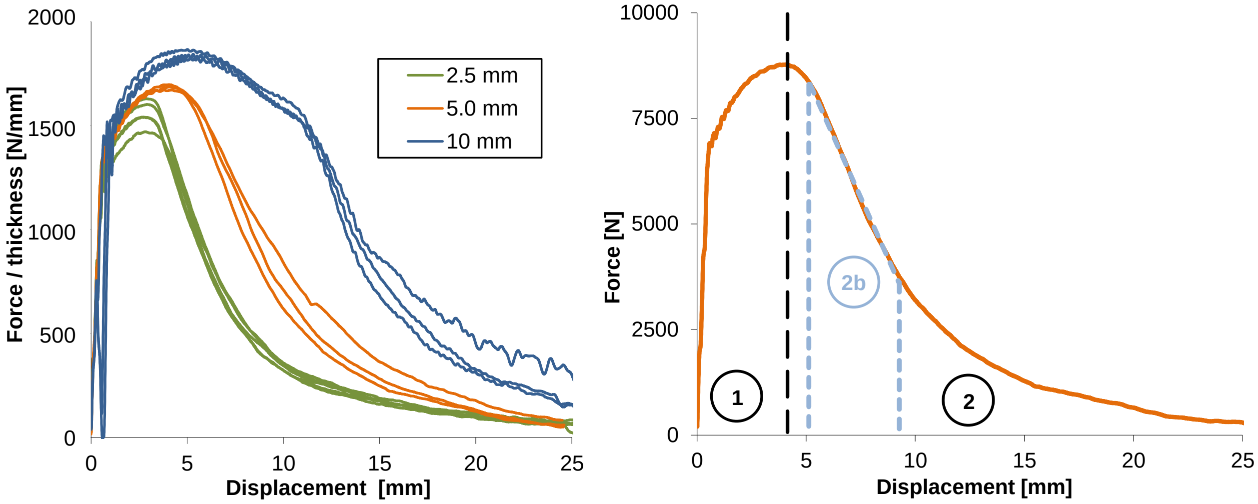

Figure 3: Left: Normalised force-displacement curves for CVN samples of 2.5 mm, 5.0 mm and 10 mm thickness at room temperature. Right: Force-displacement curve from instrumented CVN experiment on an X70 sample with a thickness of 5 mm at room temperature (fully ductile failure). Areas 1 and 2 are respectively the crack initiation and propagation regions. Area 2b is the region of linear crack propagation.

Table 1: Measured values.

Thickness [mm]	Total Specific Energy [J/cm²]	Linear propagation energy/Total Energy [%]
10	336	14.5
5.0	211	24.1
2.5	155	33.3

3 NUMERICAL SIMULATION

To obtain a better insight in the observed changes in failure mode and energy, the impact tests are simulated by finite element analysis. The ductile tearing is modelled using the Gurson-Tvergaard-Needleman (GTN) model [9]. In this model damage is represented by a variable based on the void volume fraction (which can be related to void measurements similar to those shown in Figure 2). The used numerical approach is described by the authors more in detail in [10].

The finite element model geometry is shown in Figure 4. To increase calculation efficiency, the specimen is modelled using two symmetry planes. Hence, only a quarter of the specimen is modelled. The mesh density is the highest around the notch and in the region where the crack will propagate.

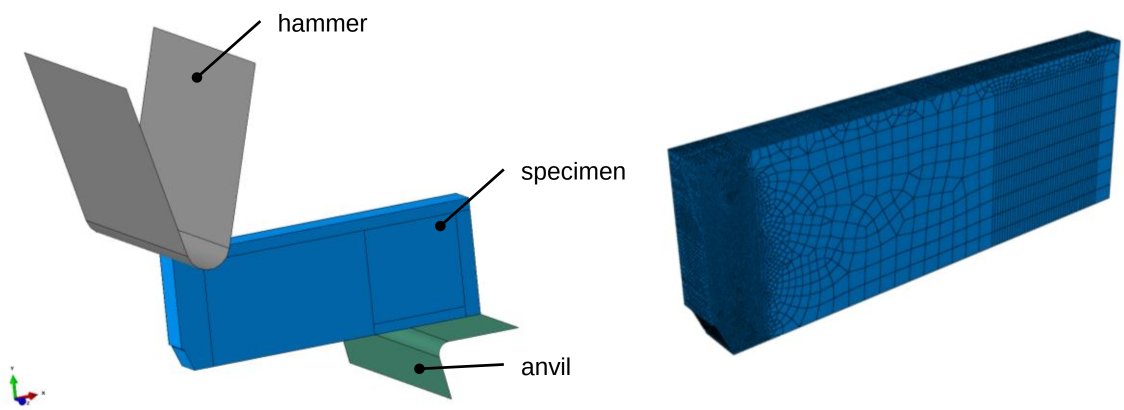

Figure 4: left: parts of FEA model; right: mesh ¼ of CVN specimen.

The von Mises stress distribution for the 10 mm, 5.0 mm and 2.5 mm models is given in Figure 5. To make the views more comprehensive, the results are mirrored around the two symmetry planes to show the full test specimens.

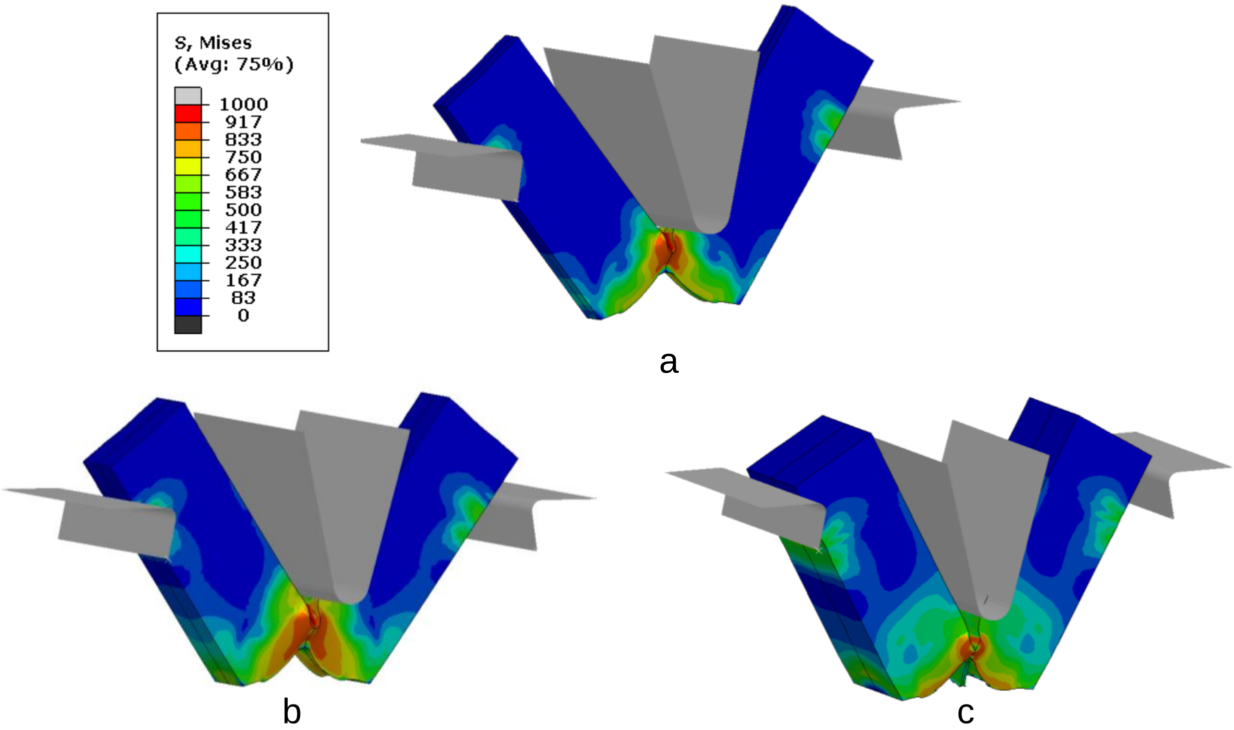

Figure 5: FEA results (von Mises stress) of CVN specimens with thickness of a) 2.5 mm, b) 5.0 mm and c) 10 mm.

4 COMPARISON BETWEEN MEASURED AND MODELLED DATA

In this section a comparison is made between the experimental test data and the results obtained from the numerical model. All simulations are carried out using the same set of GTN parameters. As illustrated by the normalized force-displacement curves in Figure 6, the simulations are able to reproduce the experimental results rather accurately. The maximum load and corresponding displacement increase when the specimen thickness is increased. However, the change in slope of the 10 mm specimens could not be explained by the simulations.

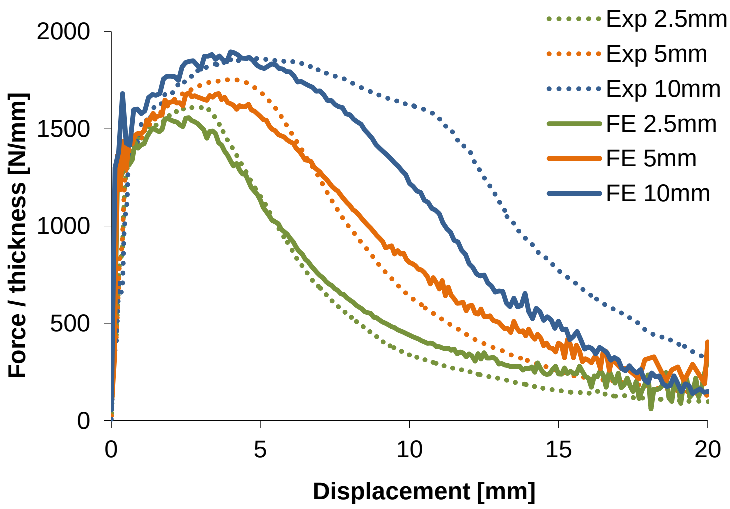

Figure 6: Comparison between modelled and measured force-displacement curves.

Figure 7 compares the modelled and experimentally obtained fracture surfaces. The finite element model predicts a failure mainly in mode I for the standard 10 mm samples and a slant failure mode for the 2.5 mm specimen. This different behaviour can be explained by monitoring the crack front evolution during the simulation. For the used X70 material, the slant failure is caused by a tunnelling of the crack at mid thickness of the specimen. Because the ligament length is larger than the specimen thickness, the fracture surfaces become tilted. Since the ratio between the ligament length and specimen thickness is smaller for the 5.0 mm specimen than for the 2.5 mm specimen, this tilting is less pronounced, but still present for the 5.0 mm specimen.

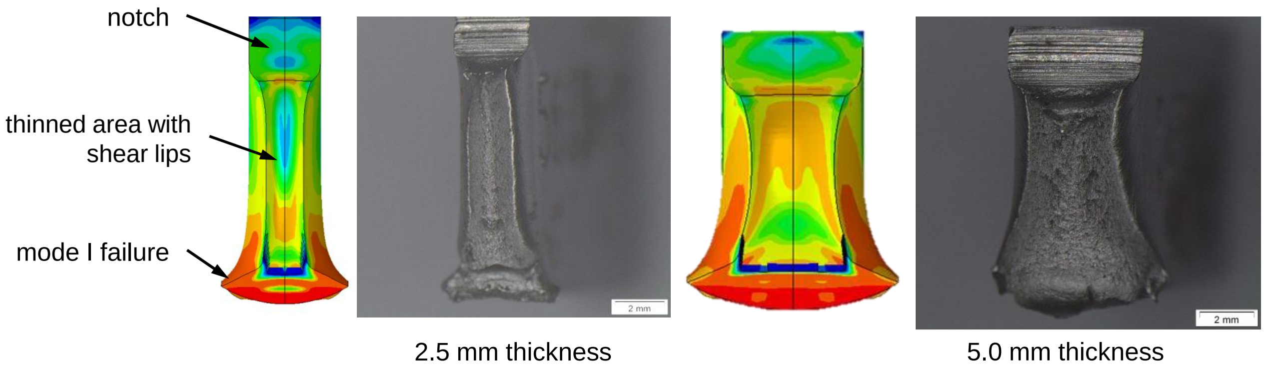

Figure 7: Comparison between modelled and experimentally obtained fracture surfaces.

5 CONCLUSIONS

In this study slant failure is promoted in Charpy impact specimens by reducing their thickness. Slant failure is obtained and by using instrumented impact tests it is shown that the reduced-thickness samples show a decreased crack initiation energy. Reducing the specimen thickness leads to a reduction of the maximum normalized impact force and a shift of this maximum to a lower displacement. The measured trends are confirmed by numerical simulations that can successfully represent the crack propagation behaviour. Due to the increased ligament/thickness ratio in the reduced-thickness specimens, the crack is tunnelled towards the mid thickness of the samples and the fracture surface becomes tilted. The numerical model is a powerful tool and can be used to further increase the understanding of pipeline slant failure.

6 REFERENCES

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