SENT (SINGLE EDGE NOTCH TESION) METHODOLOGY FOR PIPELINE APPLICATIONS

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ABSTRACT

It is well understood that fracture toughness is dependent on the crack tip constraint and testing results from single edge notch bending specimens (SENB) are too conservative for engineering critical assessment of cracked pipelines, which are characterized by thin wall thickness and relatively high toughness. There is a general trend in the pipeline industry to accept the single edge notch tension specimen (SENT) as an alterative testing specimen for better fracture assessment of both virgin and pre-strained and welded pipelines. This paper will summarize the vast experience in the last decade in Norway and present the latest systematic numerical and experimental results on the development of a SENT methodology for pipeline applications. It includes the following aspects: the theoretical background for the SENT methodology; selection criterion and the technique to fine-tune the crack tip constraint of a SENT geometry to represent the cracked pipes; effect of weld metal mismatch and misalignment; effect of internal pressure on the fracture resistance of a pipe; size dependence and independence of the SENT fracture resistance curves. The paper will end by discussing the limitation and application windows of the SENT methodology.

KEYWORDS

Ductile fracture; crack tip constraint; fracture mechanics testing; pipeline applications.

INTRODUCTION

The fundamental concept in the conventional elastic-plastic fracture mechanics is that the crack tip stress field can be described by a single parameter, the J-integral (HRR field) or crack tip opening displacement (CTOD), and material fracture toughness, usually obtained from standard bending dominated fracture mechanics testing specimens, can be transferred to engineering critical assessment of structural components. There are, however, many scenarios where the conventional single parameter approach becomes invalidated and crack tip stress fields are influenced by the loss of crack tip constraint. Here, constraint can be understood literally as a structural or material obstacle against plastic deformation, which is induced mainly by geometrical and physical boundary conditions [1]. The emphasis in fracture mechanics remains to find appropriate parameters to characterize the crack tip stress field of both small scale fracture mechanics testing specimens and full scale structural components with cracks.

For homogenous materials, the crack tip stress field is influenced by specimen dimensions, crack depth/specimen width ratio as well as loading mode. A second parameter based on the elastic *T* stress has been proposed by Betegon and Hancock [2] to describe the crack tip stress field. For elastic-plastic problems, O'Dowd and Shih [3] proposed a *J-Q* formulation to characterize the effect of geometry constraint on the crack tip stress field, where *J* sets the deformation level and *Q* is a stress triaxiality parameter which is a direct measure of the stress field that is related to a reference field usually described by the HRR field. Under small scale yield conditions it has been shown that the *Q* parameter can be uniquely linked to the elastic *T* stress. However, in finite geometries under large scale yielding, the one-to-one relation is lost.

For interface crack in a weldment, crack tip stress field will not only be influenced by the geometric constraint, but also by the mismatch between different material properties [4]. Numerical studies by Zhang et al [4] have shown that the effect of material mismatch on the crack tip stress field can be described by a material mismatch constraint parameter *M*. It has also been found that the effect of geometry and material mismatch to a certain degree is independent of each other and can be separated. Based on this observation, a so-called *J-Q-M* formulation has been proposed to characterize the effect of both geometry and material mismatch constraints on the crack tip stress field.

Recently, studies by Eikrem et al. [5], Liu et al [6] and Ren et al. [7] have shown that a prestrain history, for example induced by pipe reeling, as well as welding residual stresses will result in additional crack tip constraints. Parameters *P* and *R* have been introduced to characterize the crack tip constraints induced by plastic prestrain history and welding residual stresses. With appropriate fracture criteria, these crack tip constraint formulations provide a method to quantify the effect of geometry, loading, material property mismatch, welding residual stresses et al. on the crack initiation and growth behavior by these constraint parameters. It opens also for a new avenue in fracture mechanics where finite element method is used for assessing the fracture mechanics specimen crack tip constraint levels such that the fracture toughness obtained from laboratory small scale fracture mechanics testing can be constraint-corrected and further transferred to the engineering critical assessment of structural components.

SENT FOR PIPELINE APPLICTIONS

Due to thin wall thickness and large plasticity involved, it has become evident that fracture mechanics based engineering critical assessment of offshore pipelines using fracture toughness directly obtained from standard SENB specimen becomes too conservative. Though the constraint-correction method can be applied to the toughness data from SENB before being further transferred to the engineering assessment of cracked pipelines, it is beneficial to utilize testing specimens producing fracture toughness data which can be directly used for assessment of large scale structural components and overcome the extreme conservativeness. SENT specimen is a good alternative, see Fig. 1.

Nyhus et al. conducted a detailed 3D finite element analysis of surface semi-elliptic circumferential cracks and compared with the crack tip constraint of a SENT specimen with similar crack depths [8]. The results show that that the crack tip constraint level in cracked pipe models is rather independent of the semi-elliptic crack width (c). The crack tip constraint of a clamped SENT specimen provides a very close but slightly conservative upper-bound constraint to the pipe models, see Fig. 2. This finding suggests that the fracture toughness obtained from a fine-tuned SENT specimen can be directly transferred to the engineering critical assessment of cracked pipelines without performing a toughness correction procedure.

These findings become the basis of the DNV guidelines for engineering critical assessment for pipeline installation methods introducing cyclic plastic strains [9].

The crack tip constraint levels in SENT specimens can be fine-tuned by the loading conditions (clamped versus pin-loaded), crack/depth ratios and the length of the specimens. Fig. 3 shows the influence of loading modes (bending, clamped tension and pin-loaded tension) on the deformation modes and crack tip constraint (Q). There is a large degree of freedom to fine-tune the crack tip constraint of a SENT specimen. In general, the crack tip constraint of a SENT specimen can be increased by using pin-loading, longer specimen or deeper crack.

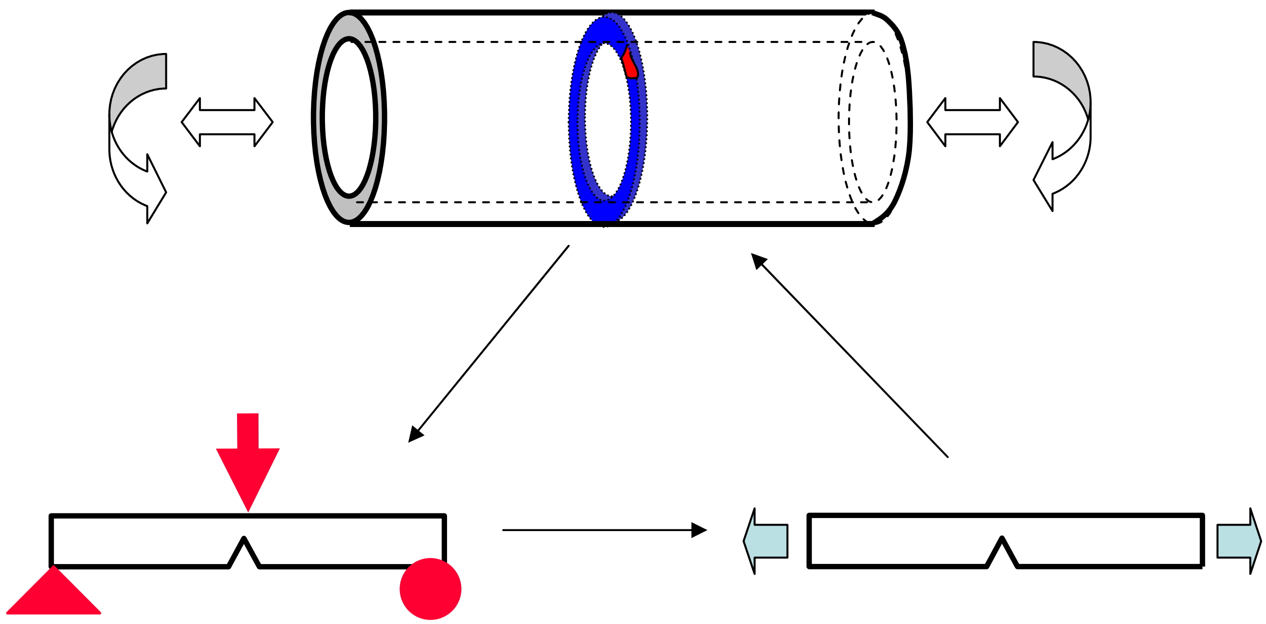

Fig. 1 Fracture mechanics testing specimens for pipeline applications: single edge notch bending specimen (SENB) versus single edge notch tension specimen (SENT).

RECENT STUDY ON SENT METHODOLOGY

Effect of pipe Internal pressure – validity of SENT specimen

Internal pressure in a pipe induces bi-axial loading. Bi-axial loading will certainly modify the crack driving force. It was not clear, however, how the fracture resistance of a pipe will be influenced by the existence of internal pressure. Ductile fracture is characterized by microvoid nucleation, growth and coalescence. High stress triaxiaility accelerates void growth and reduce the void coalescence strain. Intuitive thinking tells that biaxial loading tends to increase the crack tip constraint, and thus the fracture resistance should be reduced. Question regarding if resistance curve from a SENT specimen can be directly transferred to the engineering critical assessment of pipes with varying internal pressures should be answered. The effect of internal pressure on the fracture resistance curves of pipe models with axi-symmetrical crack has been investigated by using the complete Gurson model developed by the authors [10]. Both international and external cracks were considered.

Fig. 4 shows one example. The results show that for shallow cracks (a/t=0.1) with hoop stress (σ_h) up to 75% of the yield stress, the internal pressure has an insignificant effect on the fracture resistance curves of the pipe modes and the SENT specimen provides a very close but conservative low-bound resistance curves to the cracked pipes. This is in line with observations from large-scale testing of pipes investigating the effect of internal pressure level reported by Østby and Hellesvik [11]. The general conclusion is that the resistance curve from an appropriate SENT specimen can be applied directly to the engineering critical assessment of cracked pipe models with and without internal pressure.

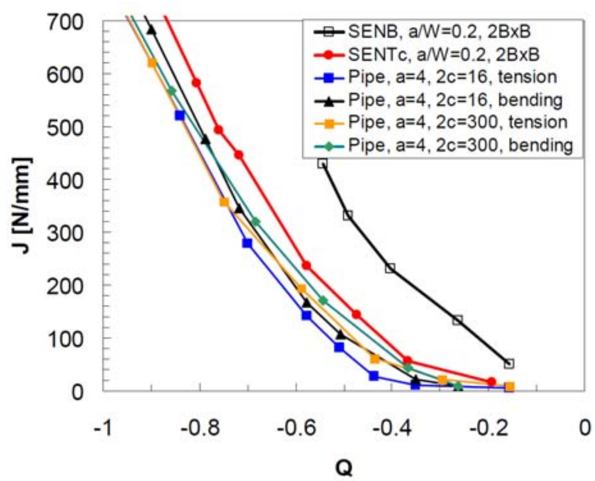

Fig. 2 Comparison of the crack tip constraint of cracked pipe models with SENT and SENB specimens [8].

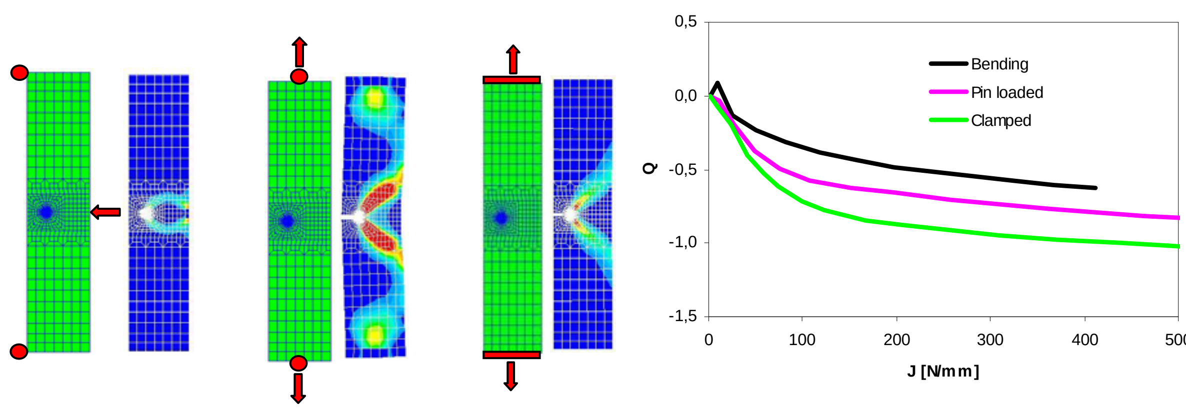

Fig. 3 Comparison of the deformation modes and crack tip constraints (Q) of the SENB specimen with the SENT specimens with different loading conditions. Both the SENB and SENT specimens have identical geometry and crack depth.

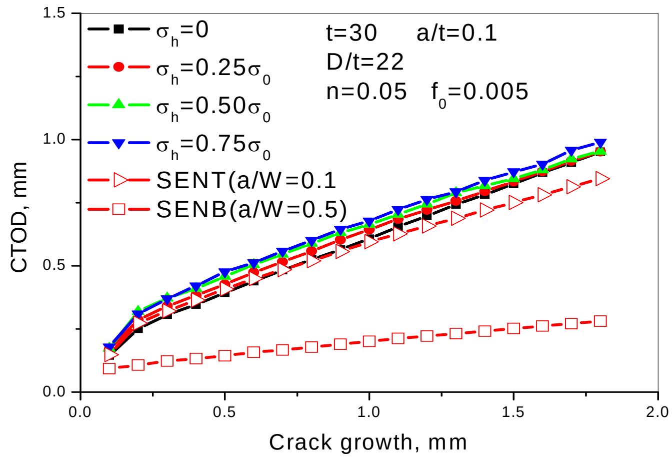

Fig. 4 Resistance curves of 2D axi-symmetric pipes under tension with a shallow crack (a/t=0.1) and various internal pressures [12]. Results of both SENT specimen (a/t=0.1) and the standard deep notched SENB specimen (a/t=0.5) are also presented for comparison. The complete Gurson model has been used for the numerical simulation. In the figure, D is the pipe diameter, t is the pipe thickness, *a* is the crack depth, *W* the specimen width, σ_h the hoop stress, f_0 the initial void volume fraction and *n* the power hardening exponent.

Selection of crack depth

There is a consensus that the width (*W*) of SENT specimens should be as close to the wall thickness of the pipe as possible. However, the selection of crack depth for the SENT specimens is an important issue. It is commonly required that the crack depth in a SENT specimen should be larger than the defect size found in the pipe. An experimental testing program carried out by Nyhus et al for the X65 pipeline steel found that the fracture toughness is somewhat independent of the crack depth (*a/w*), in the range from 0.2 to 0.55 [13]. The results open for the suggestion of a standardization of crack depth in SENT specimens.

The effect of crack depth and specimen width on the fracture resistance curves of a SENT specimen has been recently studied with the complete Gurson model [14]. Fig. 5 shows the critical CTOD values at crack growth Δa=0.5 mm for SENT specimens with various width (W) and crack depth (*a/W*). The results for SENB are also presented for comparison. It can be observed that for the SENT specimens with small width *W*=10 mm, the CTOD values become less sensitive to the crack depth for the SENT specimens. This echoes the experimental findings by Nyhus [13]. However, for larger specimens *W*= 30 and 50 mm, a clear reduction on the critical CTOD values with the increase of crack depth can be seen. It is interesting to note that the effect of crack depth is rather independent of the specimen size for the SENB specimens. Even for the smallest specimen, the reduction of the critical CTOD is distinctive.

The specimen width and crack depth effect can be explained by the constraint parameter *Q*. Fig. 6a and 6b plot the critical CTOD at 0.5 mm crack growth versus *Q* values for both the SENB and SENT specimens, respectively. Fig. 6b shows that the Q values for the smallest SENT specimens, *W*=10mm with *a/W*=0.1, 0.3 and 0.5, are highly negative and do not change significantly for different crack depths. The results indicate that the crack tip constraint level is very low and similar to each other for small SENT specimens with different crack depths. These specimens therefore exhibit an "independent" relationship between the fracture resistance and crack depth. For larger specimens, *W*=30 and 50mm, loaded in both bending and tension, the critical CTOD values decrease considerably with the increase of crack tip constraint (*Q*-parameter).

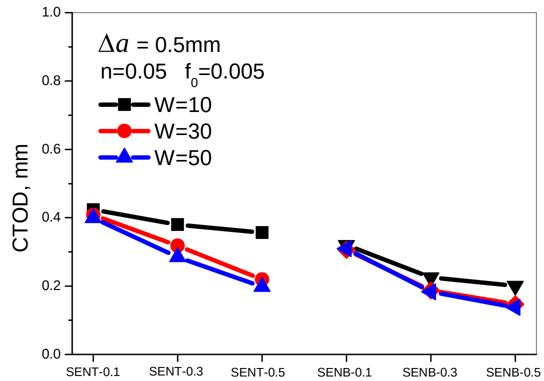

Fig. 5 Effect of specimen width (W) and crack depth (a/W) on the critical CTOD at 0.5 mm crack growth [14].

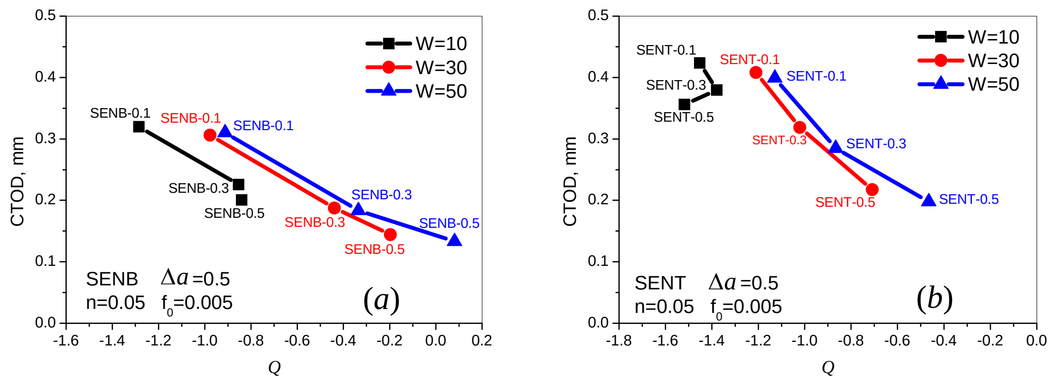

Fig. 6. CTOD-*Q* relations for SENB and SENT specimens [14]. *a* is the crack depth, *W* the specimen width, f_0 the initial void volume fraction and *n* the power hardening exponent. SENT-0.1 indicates that a SENT specimen with a/W=0.1.

Effect of prestrain history on the resistance curves of SENT specimens

During installation and operation, pipeline steels may be subject to plastic pre-deformation (prestrain) due to the actual installation method used, accidental loading, cold bending or ground movement. SENT specimens have bee used to study the effect of prestrain history on the ductile fracture resistance [15]. Preliminary results, Fig. 7 show that a plastic prestrain history can reduce the fracture resistance significantly and neither the history-independent resistance model nor material-memory resistance model existing in the literature can be used to describe the prestrain history effect. An experimental program is being carried out at SINTEF to study the effect of pre-strain history on fracture resistance behavior of pipeline steels.

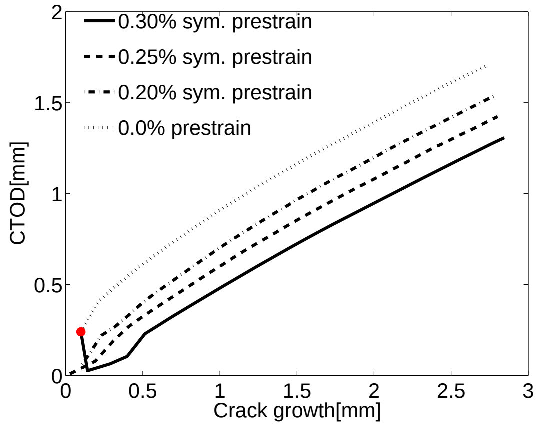

Fig. 7. Effect of prestrain history on the ductile fracture resistance of SENT specimens [15]

Effect of weld metal mismatch and misalignment

A large experimental program has been carried out at SINTEF using SENT specimens to investigate the effect of weld metal mismatch and misalignment (asymmetrical configurations) on the fracture resistance [16]. A small reduction in fracture toughness when the crack is located in the fusion line has been observed. However, within the parameters varied in the testing program, it seems that the reduction is insignificant and it can be neglected in the engineering critical assessment. Further studies are necessary to quantify the effect of weld metal mismatch and misalignment and transfer the SENT results to the engineering critical assessment of pipelines.

CONCLUSIONS

Materials apparent fracture toughness strongly depends on the crack tip constraint, i.e. different fracture mechanics testing specimens will result in a large spectrum of fracture toughness data. Pipeline steels are usually characterized by thin wall thickness and high toughness. Even a pipe under global bending the whole ligament where crack is considered is in tension. Therefore, cracked pipelines belong to low-constraint structural components. Engineering critical assessment of cracked pipelines using standard single edge (deep) notch bending specimens has shown to be too conservative and significant saving can be achieved by using fracture mechanics specimens with similar crack tip constraint to the cracked pipes. There is a general trend in the offshore industry to accept the single edge notch tension method as an appropriate testing method for producing the fracture toughness data.

A large amount of numerical simulations and experimental studies on the fracture resistances of SENT specimens and both full scale surface cracked pipes have been undertaken in Norway. It can be well concluded that the internal pressure has a minor effect on the fracture resistance curves.

When the pipeline steel toughness level is high and pipe wall thickness is small, the fracture resistances of SENT specimens become independent of the crack depth. In the DNV guidelines it is suggested that the crack depth in the SENT specimens should be larger than the crack depth found in a pipe. It seems that the crack depth is not a critical parameter for SENT testing and a standard SENT specimen can be designed for pipeline application when the pipe thickness is not large and the toughness level is high.

With the acceptance of SENT specimens for the engineering critical assessment of cracked pipe models, various effects, such as prestrain history, weld metal mismatch et al can be quantified. However, it is important to bear in mind the limitation and validity range of the SENT methodology.

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